



D.1.3.1 Report on the sustainability potential of AM technologies

Contact details

Project coordinator: Maja Mešl, maja.mesl@ftpo.eu, +386 51 315 970
 Address: Faculty of Polymer Technology (FTPO), Ozare 19, 2380 Slovenj Gradec, Slovenia

Project details

Project ID	SIAT00036
Project Acronym	ADDCIRCLES
Project Name	Promoting Sustainable Regional Development through Additive Manufacturing: A Cross-Border Initiative for a Resilient and Circular Economy
Starting date	1 November 2023
Duration in months	36
Call (part) identifier	Open Call for proposals for standard projects
Programme priority	P1-A - A more resilient and sustainable region
Specific objective	1.2 - Promoting the transition to a circular and resource efficient economy

Document details

Work Package	Joint development of innovative solutions and methodologies for Green AM
Activity	Analysing the sustainability potential of AM technologies
Deliverable number	D.1.3.1
Version	1
Filename	
Type of Deliverable	Report
Dissemination Level	Public
Work package leader	Janez Slapnik (FTPO)
Task leader	Branka Mušič (ZAG)
Author(s)	Branka Mušič (ZAG), Davor Kvočka (ZAG)
Due date	31 October 2024
Submission Date	

Version management

Revision history and quality check			
Version	Name	Date	Comment
V0.1			
V0.2			
V1			

Table of content

Table of Abbreviations.....	2
Table of Figures.....	4
1. Introduction	5
1.1. Understanding and Navigating the Additive Manufacturing Field with the Help of International Standard ...	6
1.2. Diverse Additive Manufacturing Techniques.....	9
1.3. Material Utilization in Additive Manufacturing.....	12
2. Fundamentals of LCA and Its Significance in Crafting Innovative Business Cases.....	18
3. Empowering Regional Businesses: The AddCircles Project's Role in Advancing Additive Manufacturing and the Circular Economy.....	23
3.1. Exploring Pertinent Scientific Research on Additive Manufacturing and Life Cycle Assessment.....	30
4 Best practice examples in additive manufacturing and recommendations for SMEs.....	39
4.1 Best Practice Examples in Additive Manufacturing.....	39
3.2 Recommendations for SMEs.....	44
5. Conclusions	49
6. Additional Information.....	50
6.1. Appendix 1	51
6.2. Appendix 2	53
7. Literature	55

Table of Abbreviations

This section lists the abbreviations necessary for understanding the text in alphabetical order. These abbreviations are not only relevant within the context of this booklet but also widely employed globally in scientific and professional literature, as well as on the Internet.

Given the variance in abbreviation usage across various media sources, the list below may feature multiple abbreviations for the same phrase in certain instances.

AM – Additive Manufacturing
ASTM – American Society for Testing and Materials
BJ – Binder Jetting
CFF – Continuous Fiber Fabrication
CLIP – Continuous Liquid Interface Production
CM – Conventional Manufacturing
CNC – Computer numerical control
DED – Directed Energy Deposition
DLP – Digital Light Processing
DMLS – Direct Metal Laser Sintering
EBM – Electron Beam Melting
FDM – Fused Deposition Modeling
FFF – Fused Filament Fabrication
GWP – Global Warming Potential
ISO – International Organization for Standardization
LCA – Life Cycle Assessment
LCCA – Life Cycle Cost Assessment
LOM – Laminated Object
ME – Material Extrusion
MEX – Material Extrusion
MJ (MJT) – Material Jetting
MJM – MultiJet Modeling

PBF – Powder Bed Fusion

SETAC – Society for Environmental Toxicology and Chemistry (Zavod za okoljsko toksikologijo in kemijo)

SHL – Sheet Lamination

SIST EN ISO – Slovenian Institute for Standardization (harmonized with ISO standards)

SL – Sheet Lamination

SLA – Stereolithography

SLCA – Social Life Cycle Assessment

SLM – Selective Laser Melting

SLS – Selective Laser Sintering

TRL – Technology Readiness Level

USEPA – US Environmental Protection Agency (ameriški oddelek za okolje)

VP – vat photopolymerization

VVP – vat photopolymerization

Table of Figures

Figure 1: Seven Process Categories of Additive Manufacturing Processes as defined by ISO and ASTM Standards.

Figure 2: Examples of composites based on biodegradable and non-biodegradable polymers used for additive manufacturing

Figure 3: Polymer selection due to the additive manufacturing

Figure 4: Additive manufacturing and the material feedstock state possibilities

Figure 5: The main stages of LCA

Figure 6: A tabular record of the components of SLS, ME, DMLS, and FDM

Figure 6a: A schematic representation of SLS, SLM, and DMLS

Figure 7: A tabular record of the components of ME and FDM

Figure 6: A tabular record of the components of SLS, ME, DMLS, and FDM

Figure 6a: A schematic representation of SLS, SLM, and DMLS

Figure 7: A tabular record of the components of ME and FDM

Figure 7a: Scheme of screw-based additive manufacturing material extrusion

Figure 7b: Scheme of plunger-based additive manufacturing material extrusion

Figure 7c: Scheme of filament-based additive manufacturing material extrusion

Figure 8: Life cycle assessment value chain for additive manufacturing

1. Introduction

Terms, such as digitization, 4.0 industries, Life Cycle Assessment (LCA), Life Cycle Cost Assessment (LCCA), recycling, environmental impact, sustainability, etc., are often intertwined nowadays.

Sustainability is a fundamental principle guiding contemporary industrial practices. It involves meeting present needs without compromising future generations. So, achieving sustainability involves minimizing adverse environmental impacts.

On the other hand, industry 4.0 is characterized by the integration of digital technologies, automation, and data exchange in manufacturing processes that contributes to sustainability by optimizing resource utilization, reducing waste, and enhancing efficiency through smart technologies and data-driven decision-making. AM is a key component of Industry 4.0 and enables the production of complex, customized components with reduced material waste compared to traditional manufacturing methods fostering flexibility, on-demand production, and decentralized (local) manufacturing processes that minimize transportation-related emissions and promote sustainable supply chain practices which lead to better LCA and sustainability. Sustainability efforts benefit from LCA by providing a comprehensive understanding of a product's environmental footprint, aiding in the identification of areas for improvement that are the base of social progress.

In essence, the amalgamation of sustainability, environmental impact considerations, Industry 4.0, additive manufacturing, and LCA reflects a holistic approach to modern industrial practices. This integration aims to not only enhance efficiency and innovation but also to ensure that industrial processes are aligned with acceptable and long-term environmental goals.

1.1. Understanding and Navigating the Additive Manufacturing Field with the Help of International Standard

There are many variations of 3D printing and new technologies emerge as the field continues to evolve, which can cause some confusion in understanding AM techniques. Additionally, during the development of additive manufacturing technology, there have been numerous different terms and definitions in use, often with reference to specific application areas and trademarks. The AM (3D processes) are standardized and the AM classification according to the International Organization for Standardization/ American Society for Testing and Materials (ISO/ASTM) is given below¹.

In the standard (ISO/ASTM 52900:2022), it is noted that AM is the general term for technologies that successively join material to create physical objects as specified by 3D model data. These technologies are presently used for various applications in the engineering industry as well as other areas of society, such as medicine, education, architecture, cartography, toys, and entertainment.

According to The International Organization for Standardization (ISO)/American Society for Testing and Materials (ASTM) 52900:2022, AM is classified into seven categories² (Figure 1):

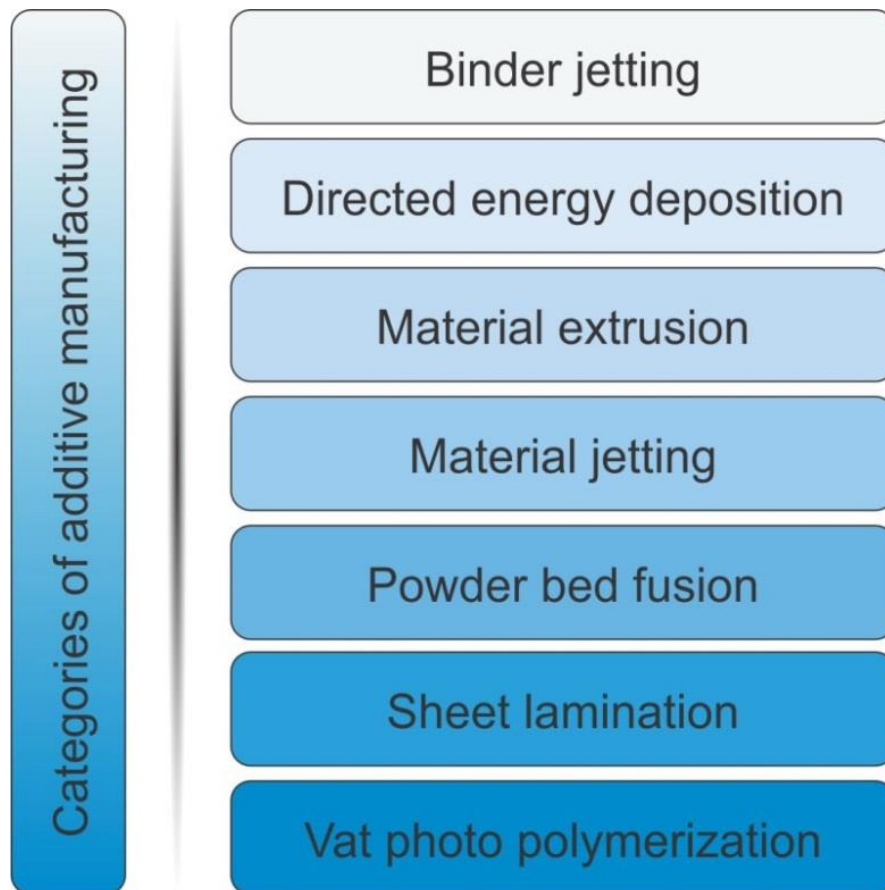


Figure 1: Seven Process Categories of Additive Manufacturing Processes as defined by ISO and ASTM Standards.

(1) Binder Jetting is defined as an AM process in which a liquid bonding agent is selectively deposited to join powder materials.

(2) Directed Energy Deposition (DED) is defined as an AM process in which focused thermal energy is used to fuse materials by melting as they are deposited.

(3) Material Extrusion (ME/MEX) is defined as an AM process in which material is selectively dispensed through a nozzle or orifice.

(4) Material Jetting (MJ/MJM/MJT) is the selective spraying or deposition of droplets of material, usually a liquid photopolymer, onto a build platform, which then solidifies or cures. Examples of processes in this category include PolyJet and MultiJet modeling.

(5) Powder Bed Fusion (PBF) is defined as the process in which thermal energy selectively fuses regions of a powder bed.

(6) Sheet Lamination (SL/SHL) is an additive manufacturing process in which sheets of metal are bonded to form an object.

(7) Vat Photopolymerization (VP/VPP) is currently a widely used rapid 3D-printing method³.

These seven categories cover most of the AM technologies, with the classification provided by ISO/ASTM. The last and most recent is the SIST EN ISO/ASTM 52900:2022, Additive Manufacturing – General Principles – Fundamentals and Vocabulary.

The purpose of this document is to provide a basic understanding of the fundamental principles for additive manufacturing processes, and based on this, to provide clear definitions of terms and nomenclature related to additive manufacturing technology. The aim of this standardization of additive manufacturing terminology is to facilitate communication between all stakeholders involved in this technological field. The further goal of the document is also to present the basics of LCA as an effective tool for assessing the impact of products on the environment, to present a summary of the literature review on AM environmental impacts, to provide a list of product groups with the greatest potential for optimization, and to provide examples of good practice and to combine recommendations from the literature for small and medium-sized enterprises (SMEs) in implementing AM.

1.2. Diverse Additive Manufacturing Techniques

AM allows the creation of complex models directly from digital models. This digital-to-physical translation not only simplifies the manufacturing process but also facilitates the implementation of smart manufacturing practices, including real-time monitoring, predictive maintenance, and quality control. This is the reason that so many different methods have been developed in practices which additionally affect the efficiency of AM production.

As an introduction, we list some of the main AM techniques we have encountered in our state-of-the-art review. Each of them has its advantages. The choice of which technique to use depends on factors, such as material requirements, accuracy, printing speed, and the specific use of the printed object.

It is crucial to emphasize that newer methods persistently emerge amidst the constant and rapid advancements. Staying abreast of these innovations is vital to remain current in the field.

1. Powder Bed Fusion (PBF) is a broad category of additive manufacturing processes where a layer of powdered material is selectively fused to create a 3D object. This category includes several techniques, such as Selective Laser Sintering (SLS), Selective Laser Melting (SLM), and Electron Beam Melting (EBM). In all of these processes, a laser or electron beam selectively fuses the powdered material layer by layer to build the final object.

a) Selective Laser Sintering (SLS) utilizes a high-power laser to sinter (heat and fuse) powdered materials, typically nylon or other polymers. It can create strong and durable parts and is often used in industrial settings.

b) Selective Laser Melting (SLM) is a metal 3D printing technology that offers several advantages, making it a popular choice for producing metal parts in various industries.

c) Electron Beam Melting (EBM) is used for 3D printing metal parts. It employs an electron beam to melt metal powder layer by layer in a vacuum, resulting in strong and dense metal components.

PBF, often named Powder layer fusion, uses a layer of powdered material, often metal or polymer powder, and selectively melts or sinters the powder using a heat source (laser or electron beam).

2. Material extrusion (ME/MEX) AM is known for its simplicity, cost-effectiveness, and versatility in working with various materials. It is a common technique in AM, and it involves building 3D objects by extruding material through a nozzle or nozzle-like apparatus. It is commonly used in desktop 3D printers and industrial additive manufacturing systems. Some popular methods and technologies within material extrusion AM include:

a) Fused Deposition Modelling (FDM) is one of the most well-known and widely used material extrusion techniques. It works by heating and extruding a thermoplastic filament through a nozzle, depositing layer upon layer to create the final object. Popular 3D printers like those produced by MakerBot and Ultimaker use FDM technology. Fused Filament Fabrication (FFF) is a term used interchangeably with FDM, and it essentially refers to the same process of material extrusion. FFF/FDM has several advantages, e.g. generally, printers are more affordable compared to other additive manufacturing technologies, can utilize a variety of thermoplastic materials, including PLA, ABS, PETG, and more, and ease of use, making it a widely adopted 3D printing technology for both professional and hobbyist use.

b) Melt Extrusion Printing. This method is similar to FDM but can involve a broader range of materials not limited to thermoplastics. It includes using materials like wax, chocolate, or ceramics in a melted state to build objects.

c) Pellet Extrusion. In this variant of material extrusion, plastic pellets are used as the feedstock instead of filament. The pellets are melted and extruded through a nozzle to create the 3D object.

d) Continuous Fiber Fabrication (CFF) is an advanced form of AM that combines traditional 3D printing with continuous fibers, typically carbon or fiberglass. This technology offers several advantages for creating strong and lightweight composite parts.

3. Bath photopolymerization: A liquid photopolymer resin is selectively hardened or cured using a light source, usually laser or UV light. Examples of processes in this group include:

a) Stereolithography (SLA) uses a UV laser to cure a liquid resin layer by layer. This technique produces highly detailed and accurate prints and is often used in applications requiring precision, such as dental models and jewelry.

b) Digital Light Processing (DLP) is similar to SLA but uses a digital light projector to cure an entire layer of resin simultaneously. It is known for its speed and is used in various industries, including dentistry and jewelry making.

4. Direct Metal Laser Sintering (DMLS) is a metal 3D printing process that uses a high-power laser to sinter metal powder. It is commonly used in aerospace, automotive, and medical industries for producing complex metal parts.

5. Binder Jetting involves selectively depositing a liquid binding agent onto a powdered material (metal, sand, ceramic, etc.) layer by layer. This technique is often used for producing metal parts and sand molds for casting.

6. Material Jetting (MJ) 3D printers operate similarly to inkjet printers but deposit droplets of liquid photopolymer onto a build platform. These droplets are then cured with UV light to create the final object. Material jetting can produce high-resolution and multi-material prints.

7. Laminated Object Manufacturing (LOM) builds objects by layering and adhering sheets of material, often paper or plastic, which are then cut or fused using lasers or other methods. LOM is less common than some other techniques but is suitable for certain applications.

8. Continuous Liquid Interface Production (CLIP) is a proprietary 3D printing technology that uses light and oxygen to cure liquid resin continuously, enabling faster and more efficient printing.

AM technology began to be intensively developed and introduced in the early 1980s and 1990s. As we can see now, there are many AMs that came later. Companies and industries have since adopted many AM processes to better achieve their production goals. Therefore, development and growth in this area is naturally to be expected.

1.3. Material Utilization in Additive Manufacturing

The materials used in 3D printing are just as important as the printers themselves.

Based on the type, the 3D printing (AM) materials market has been classified into plastics, ceramics, and others which include wax, lay wood, bio-materials, and a variety of metals⁴. In 2022, it was observed that the metal segment accounted for the highest share of nearly 56% and the plastics segment accounted for the second largest share in the 3D printing materials market.

AM's ability to use a variety of materials, including recycled ones, is in line with the growing emphasis on circular economy practices, which is also supported by the AddCircles project. By promoting the reuse of materials and reducing the amount of waste, additive technology contributes to a more sustainable and environmentally friendly production ecosystem. Thus, numerous articles on the "Circular economy of 3D printing" are supported by various sources^{5, 6, 7, 8}.

Also, as an example we can explicitly state the recycling metal powders in additive manufacturing processes like laser powder bed fusion (LPBF) offers significant sustainability benefits by reducing waste and minimizing the environmental impact. However, it requires careful management to ensure the recycled powder maintains consistent quality and properties^{9, 10}, because the powder contamination during manufacturing can impact powder quality and consequently affects critical parameters like layer thickness and density in LPBF, which impacts part resolution and mechanical properties¹¹. The lab testing for quality assurance causes delays, so the manufacturers often discard usable powder to be safe. Important is that reusing and recycling metal powders can drastically minimize carbon footprint and promote a circular economy. A typical LPBF build may only use 20% of the available powder, so recycling the remaining 80% reduces waste. Finally, metal powders used in LPBF are often expensive, so recycling has financial benefits.

There are also a number of other scientific articles available on the subject of recycling in AM, which are very well summarized in article *Advancing Plastic Recycling: Challenges and Opportunities in the Integration of 3D Printing and Distributed Recycling for a Circular Economy*¹², which defines, among other things, comprehensive summary of published review articles, recent studies investigating the stages and challenges of plastic recycling, together with a breakdown of operating costs distributed recycling center, etc. This review article lists numerous references (approx. 250) that support this research.

As known, the polymers and their composites are now widely used in several industrial sectors, owing to their flexibility in developing customized products. The significant surge in plastic usage has led to a severe challenge in managing end-of-life plastic waste. In the study *Additive manufacturing for sustainability, circularity and zero-waste: 3DP products from waste plastic bottles*¹³, a sustainable route to converting plastic waste into AM feedstock is presented, where waste plastic bottles (mainly Polyethylene Terephthalate, PET) are recycled using an in-house 3D-printed filament extrusion system to produce filaments for fused filament fabrication (FFF) process. In addition to the recycled PET (rPET), virgin carbon fiber reinforced polyamide-6 (PA6-CF) polymer composites were also used to produce hybrid feedstock filaments. The rPET and rPET/PA6-CF composite filaments were extruded using an in-house filament extruder setup. The rPET demonstrated better failure strain and young modulus, demonstrating their potential as viable materials for industrial and consumer applications. The outcomes of this study revealed promising results to promote sustainable production and consumption, complementing the circular economy practices with a straightforward production route to convert plastic waste into AM feedstock.

Some challenges in the full-scale utilization of additive manufacturing techniques are still unsolved¹⁴. Many breakthroughs are happening in the advancement of new materials specifically designed for 3D printing, such as composite material extrusion where some advanced material extrusion systems can work by mixing different types of materials or incorporating reinforcing into the print, and bioprinting where extrusion materials are also used to create 3D structures with living cells, and biomaterials which are used in medicine and tissue engineering.

According to Bromberger et al., some of the challenges include improving the speed, end-to-end automation, and integration with existing manufacturing systems, addressing issues around certification, availability, and cost of materials, and building the skills and processes to use these rapidly evolving technologies¹⁵. Additionally, materials used in AM must meet requirements, such as being able to melt and solidify repeatedly, having a consistent particle size, and being able to flow smoothly through the printer nozzle. Therefore, the material issues for additive manufacturing technologies include limited material selection compared to traditional manufacturing processes and fewer established material standards, which can pose challenges, especially in safety-critical applications, such as aerospace and medical devices¹⁶. Additionally, variations in part quality can arise from factors, such as material chemistry, leading to the need for more materials with consistent properties. Addressing these material

issues is crucial for accelerating the use of additive manufacturing in production and ensuring the technology's competitiveness with traditional manufacturing methods¹⁷.

Also, Guggenbiller et al.¹⁸ wrote about advancements in 3D printing technology toward sustainability and green manufacturing, particularly focusing on utilizing natural and renewable materials. Additive manufacturing of natural products is gaining momentum with a focus on exciting chemistries or modifications of natural products. Employed strategies include processing natural or bioderived polymers into filament for extrusion-based 3D printing, designing photopolymer resins and inks for different printing processes, and using powders for selective laser sintering. The review explores the materials suitable for 3D printing, their physical properties, and resultant applications, including strengths and limitations. In several tables, they provide a list of green materials that can be used for VP, SLA, DLP, SLS, and FFF printing methods and point out various advantages related to environmental sustainability, their recycling aspects, or comparing non-green materials to green. Future opportunities lie in biomaterials and medical devices, electronics and batteries, and environmental remediation and water purification. Related studies on sustainable energy storage and UV-curing bio-based thermosets are also cited.

Several 3D printing materials companies focus on developing new materials like BASF¹⁹ and Evonik Industries²⁰, which are emerging companies in this field of 3D materials. 3D printing materials companies like General Electric, Sandvik, Höganäs, and Carpenter Technology only cater to the 3D printing metals market, but they are focused on high-end industries, such as the aerospace and industrial goods market. Also, other 3D printing materials companies like Materialise, Henkel, Proto Labs, Formlabs, Arkema, and Markforged (PEKK and composite materials for high-end applications) offer a wide range of products including metals, plastics, and ceramics for the 3D printing market.

The development of new 3D printing materials is expected to help 3D printing methods expand their application areas in niche sectors, such as printed electronics and energy and power industries. For instance, in 2023, Stratasys launched a new FDA-cleared resin for dental 3D printing. TrueDent resin is a monolithic, full-color 3D printed permanent denture solution that is designed to eliminate several barriers, occurring in the dental industry, such as customization and personalization, improved esthetics, and enhanced patient experience²¹.

In summary, material utilization in additive manufacturing is a rapidly evolving field that offers numerous opportunities for the production of a wide range of products from various materials

like oil-based, bio-based, bio-degradable, secondary raw materials, recycled, composites (another rapidly emerging class), etc. (Figure 2).

Composites	Biodegradable	Polymer blends	Polylactic acid, Polycaprolactone, Polyhydroxybutyrate, Polybutylene succinate, Polylactic-co-glycolic acid
		Polymer ceramic composites	Beta-tricalcium phosphate, Zirconia, Alumina, Hydroxyapatite
		Natural fillers in composites	Wood and Wood flour, Bamboo wood and powder, Sugarcane, Kenaf, Cork, Pinus radiata wood chips, Cocoa shell
		Natural fibres in composites	Harakeke, Hemp, Jute fibre, (Continuous) flax fibre, Thermomechanical pulp, Natural cellulose fibre
	Non-biodegradable	Polymer blends	Polyethylene, Polyethylene terephthalate, High-density polyethylene, Polypropylene, Polystyrene
		Polymer metal composites	Iron, Magnetic iron, Aluminium, Brass copper
		Fibre reinforced composites	Short fibre: Carbon fibre Long fibre: Glass fibre, Kevlar fibre
		Nano composites	(Multi-walled) carbon nanotubes, Nano clay, Barium titanate

Figure 2: Examples of composites based on biodegradable and non-biodegradable polymers used for additive manufacturing

It is evident that the selection of a binder (polymer) as the carrier medium for the material relies heavily on the chosen AM process available or preferred and vice versa. The following Figure 3 outlines some various polymer options for selection, contingent upon the specific AM process, their compatibility of material bonding reactions, and further in Figure 4 the material possibilities with feedstock state²².

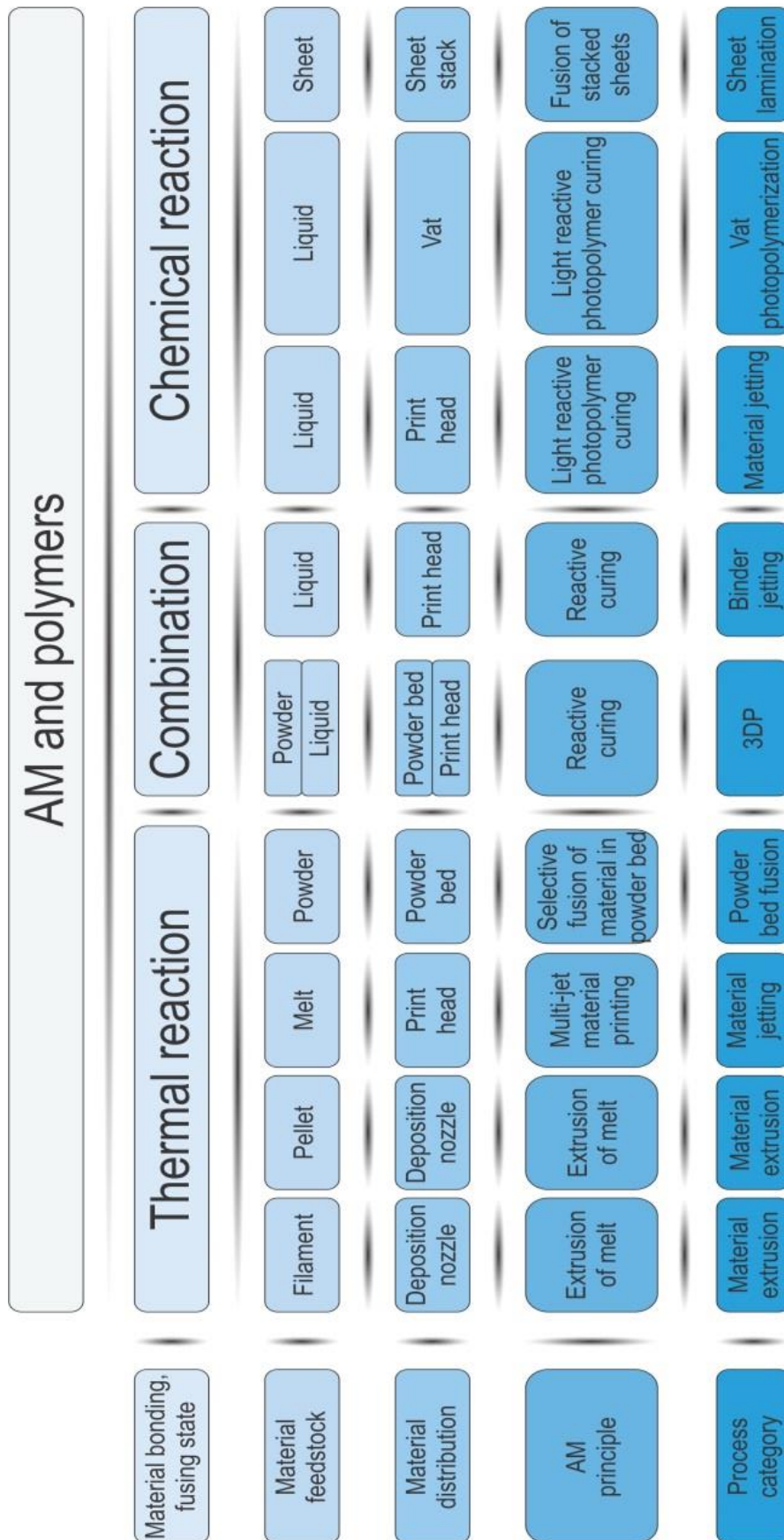


Figure 3: Polymer selection due to the additive manufacturing

AM of polymers			Feedstock state		
Process category	AM technique	Abbreviation	Solid-bulk	Solid-powder	Liquid
Material extrusion	Fused filament fabrication	FFF	x		
	Fused granular fabrication	FGF	x	x	
	Robocasting	/	x		x
Material jetting: thermal bonding of the material	Multijet modelling	MJM			x
	Ballistic particle manufacturing	BPM			x
	Thermojet	/			x
Powder bed fusion	Selective laser sintering	SLS		x	
Binder jetting	3D printing	3DP		x	x
	Binder jetting	/			x
Material jetting: chemical bonding of the material	Stereolithography	SLA			x
	Digital light processing	DLP			x
	Continuous liquid interface production	CLIP			x
Vat photo-polymerization	Multi-photon polymerization	MPP			x
	Two-photon polymerization	2PP			x
Vat photo-polymerization	Laminated object manufacturing	LOM	x		
	Solid foil polymerization	SFP	x		

Figure 4: Additive manufacturing and the material feedstock state possibilities

2. Fundamentals of LCA and Its Significance in Crafting Innovative Business Cases

LCA is a methodology that addresses the environmental impacts associated with different stages of the life cycle of a product. These stages include raw material extraction, delivery of extracted resources to the factory, material processing and manufacturing of the product, product use, repair and maintenance, and finally product reuse, recycling, or final disposal. Due to its holistic approach, LCA avoids problem shifting between both environmental impact categories and life cycle stages. Therefore, LCA is a valuable tool in various fields, such as product or process design, decision-making in industry and policy, and marketing.

The principles and framework for LCA are defined in the international standards ISO 14040²³ and ISO 14044²⁴. LCA study consists of four distinct phases:

- **The goal and scope definition phase** sets out the context of the study by defining functional or declared units, system boundaries, and any assumptions and limitations of the study.
- **The inventory analysis phase** creates an inventory of input and output flows to and from the studied system, such as inputs of water, energy, and raw materials, and outputs to air, land, and water.
- **The impact assessment phase** aims to evaluate the significance and magnitude of potential environmental impacts based on the inventory analysis flow results.
- **The interpretation phase** is where the findings from the results of the inventory analysis phase and/or the impact assessment phase are summarised and evaluated in relation to the defined goal and scope of the study.

All phases are interdependent, e.g., the gathered life cycle inventories have to fit the goal and scope with respect to time and space. In practice, this interdependence renders LCA an iterative approach because data availability is often not fully known at the beginning of an LCA study. Furthermore, the entire life cycle assessment framework is influenced by its supposed direct applications and the other way around²⁵.

Figure 5 shows the main stages of LCA and the ecological parameters for which it is necessary to collect information on environmental impacts which are then studied and evaluated using the LCA method.

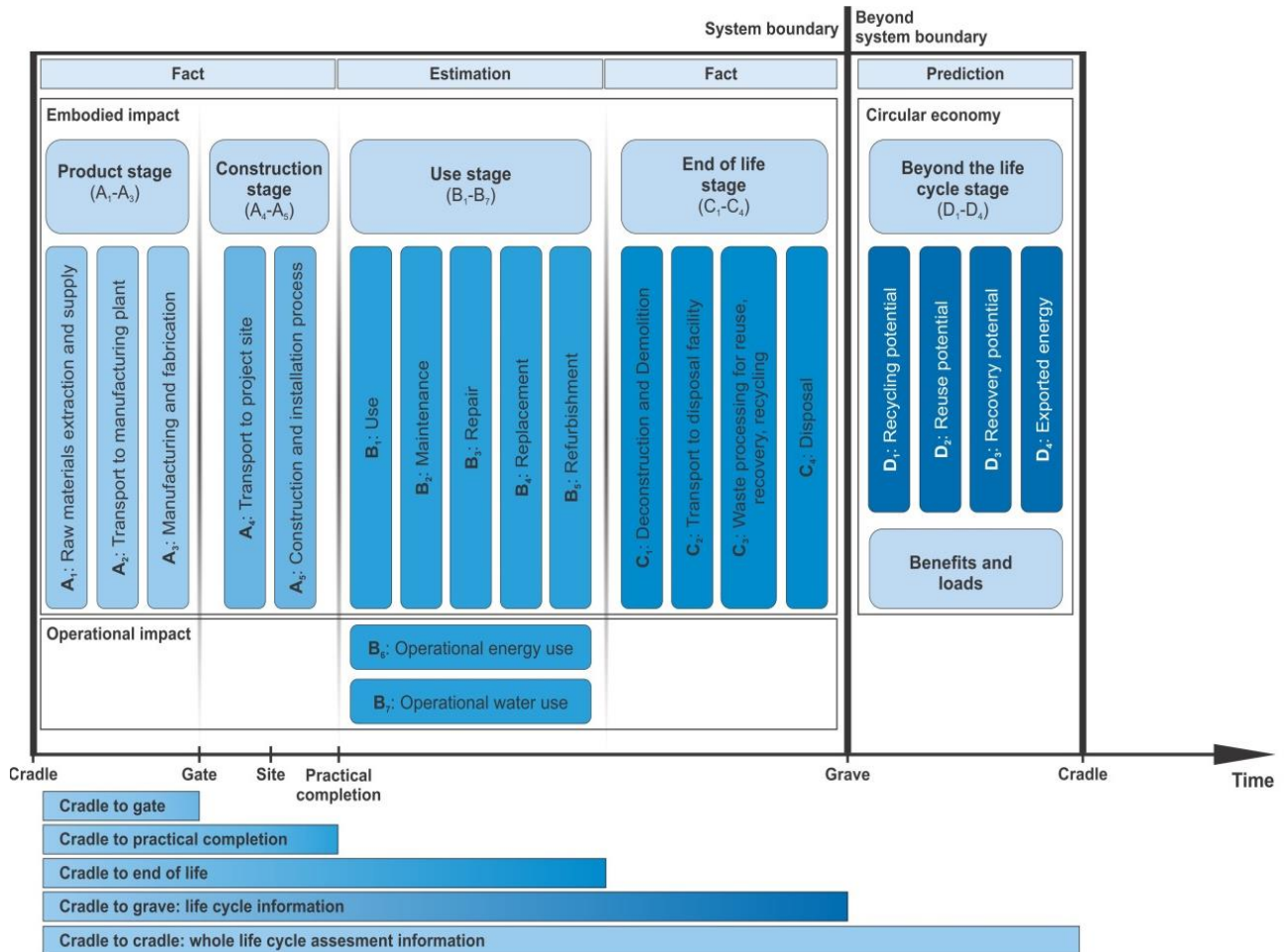


Figure 5: The main stages of LCA

Generally, an LCA study begins with an explicit statement of the goal of the study, which sets out the context of the study, outlines reasons for carrying out the study, and explains how the results are to be communicated. Following the goal, the scope must be defined by outlining the qualitative and quantitative information included in the study, such as the definition of the functions of the product system and functional or declared unit, system boundaries and allocation procedures, as well as environmental impact assessment methodology, interpretation procedure, any assumptions and limitations, and data quality requirements.

Different types of LCA analysis can be conducted:

- (i) **gate-to-gate**, which assesses the environmental impacts of a single production step or process,
- (ii) **cradle-to-gate**, which assesses a partial product life cycle from resource extraction (“cradle”) to the factory gate (i.e., before it is transported to the consumer),
- (iii) **cradle-to-completion**, which assesses a partial product life cycle from resource extraction, manufacturing, and the transport of materials to the site together with the emissions generated during construction,
- (iii) **cradle-to-grave**, which assesses the full life cycle assessment from resource extraction (“cradle”) to the use phase and disposal phase (“grave”), and
- (iv) **cradle-to-cradle**, which is a specific kind of cradle-to-grave assessment where the end-of-life disposal step for the product is a recycling process, i.e., the recycling process is used to make materials or components reusable for another product (“closing the loop”).

The type and strategy for the data to be collected have to be planned from the earliest stages of the LCA study. Depending on the foreground and background system of the study, it can be decided whether to collect site-specific data for important processes and/or averaged data for less crucial aspects of an LCA analysis. The collection of averaged data can be taken directly from LCI databases. However, the collection of site-specific data usually needs more time because it involves many different actions, such as measurements, contacting different stakeholders, organizing and attending meetings to reach companies, professionals, and other partners, etc. Therefore, gathering quality data can be a time-consuming process and thus requires active collaboration between LCA practitioners and project partners. The LCA has significance in crafting innovative business cases by assessing the life cycle of products. It will be possible to predict possible improvements concerning the environment because it helps in identifying and avoiding burden-shifting and it enables users to determine the best methods for reducing environmental burdens²⁶.

The evaluation of the environmental performance of a product should not be viewed only as an increase in the sustainability awareness desire of producers and users but also as an important marketing advantage. It is highly recommended to use LCA together with LCCA^{27,28} because this approach supports more informed decision-making in line with long-term environmental and economic goals²⁹.

LCCA considers all costs associated with a project or product, including acquisition, manufacturing, operation, maintenance, and disposal costs. The goal of LCCA is to provide a comprehensive picture of the financial implications of a project over its entire life span, covering direct costs (or "private costs") and secondary (or "external") costs.

Direct costs encompass expenses directly associated with the production of individual products, including the transportation of goods, assembly, and disassembly of products, as well as maintenance and recycling. These costs can be categorized as follows:

1. **Production and Raw Material Preparation Costs:** This includes expenses related to the production and preparation of raw materials integral to the manufacturing process of a specific product. Examples encompass electricity, fuel, employee salaries, and depreciation.
2. **Transportation Costs** encompass fuel costs, wages of transport operators, and depreciation of transportation means. These expenses pertain to the logistics of moving goods from one location to another.
3. **Assembly Costs** involve salaries, utilization of equipment for tasks conducted at elevated heights, and electricity, assembly costs account for expenditures linked to putting together the components of a product.
4. **Maintenance Costs:** These cover energy expenses and reproductive materials needed for the regular maintenance of production equipment and facilities.
5. **Removal or Recycling Costs** encompass the use of trucks, wages of workers involved in removal or recycling activities, and the utilization of landfills or incinerators. These costs are associated with the proper disposal or recycling of products.

Secondary costs emerge within production processes as adverse effects that impact economic, social, and environmental systems, as well as the relationships between economic sectors, production and environment, and producers and consumers. These costs manifest in both monetary and technological dimensions. Notably, they fail to account for the negative implications that energy production may have on human health and the environment. Examples of secondary costs include the generation of CO₂ and SO₄ emissions in exhaust gases during the combustion of engines or from the production of electricity. Additionally, these costs encompass the consequences of waste generation, and the damages caused by noise pollution.

LCA and LCCA are valuable tools for promoting sustainability and guiding decision-making towards more environmentally friendly practices.

3. Empowering Regional Businesses: The AddCircles Project's Role in Advancing Additive Manufacturing and the Circular Economy

Direct uses of LCA for regional businesses, enterprises, and AM users are:

1. development and improvement of products,
2. strategic planning,
3. guidance for policymakers (environmental and others), and
4. marketing.

The AddCircles project's role in advancing regional business both circular economy and the AM reflects its state-of-the-art approach to promoting sustainability, which requires a review of scientific publications, findings, and thus also the TRL overview of various AM technologies, bottlenecks, and hot spots in this area.

AddCircles mainly focuses on AM techniques listed below:

1. PBF, focusing on Selective Laser Sintering (SLS),
2. Material Extrusion (MEX) AM, focusing on Continuous Fiber Fabrication (CFF)
3. Direct Metal Laser Sintering (DMLS)

Below, we offer a tabular record of the components and schematic representations of SLS, SLM, DMLS (Figure 6 and Figure 6a), MEX, and FDM (Figure 7, Figure 7a, Figure 7b, and Figure 7c) additive manufacturing technologies.

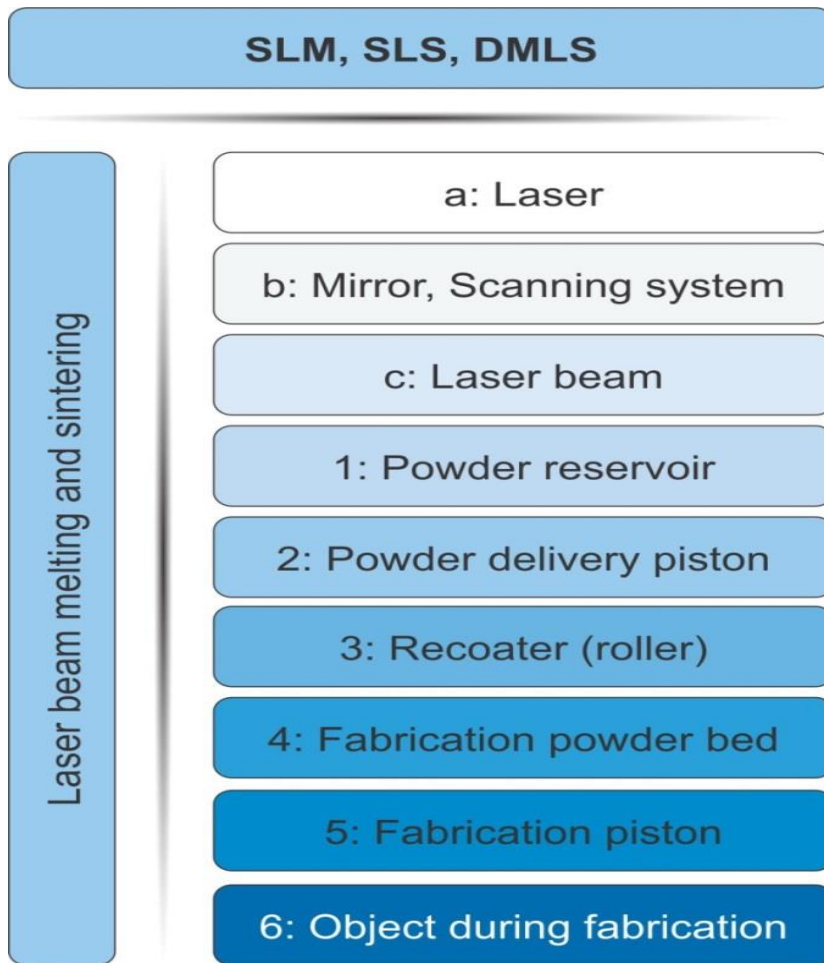


Figure 6: A tabular record of the components of SLS, ME, DMLS, and FDM

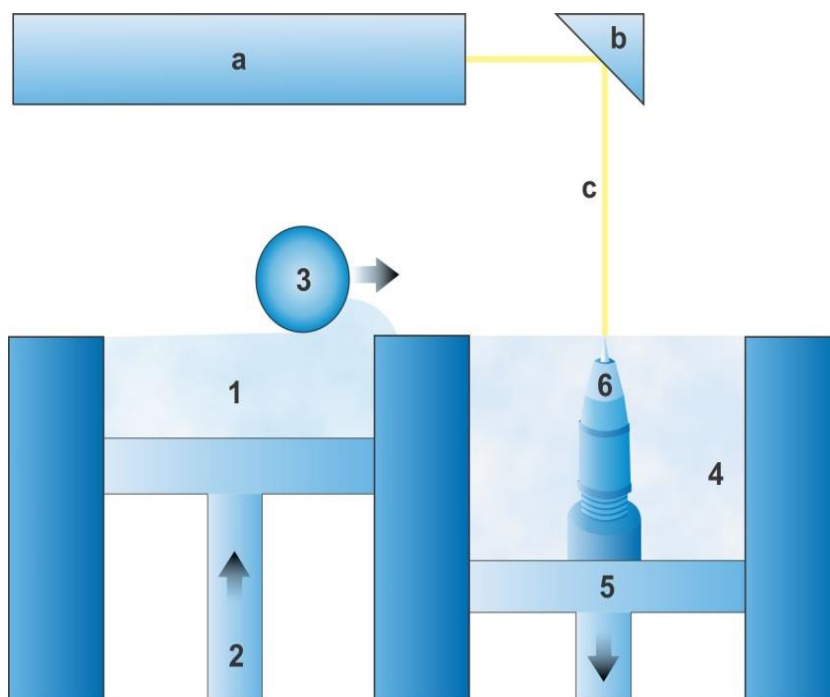


Figure 6a: A schematic representation of SLS, SLM, and DMLS

Specific energy consumption data for individual AM techniques is not freely available online but it is understood that metal additive manufacturing techniques, such as DMLS, typically have higher energy requirements compared to SLS techniques that print plastic-based materials.

SLM process is ideal for pure metals like titanium or aluminum and requires a higher temperature than other metal 3D printing techniques like DMLS. DMLS is capable of printing high-strength functional metal parts but is found to be significantly more expensive than SLS with higher energy requirements and more expensive raw materials³⁰. An energy performance benchmark for evaluating the energy efficiency of selective laser melting processes was discussed in a study by Hu et al., 2023³¹. Also, ISO/ASTM 52910:2018 standards include energy efficiency by dealing with optimizing material use, weight, and stress concentrations in designs³².

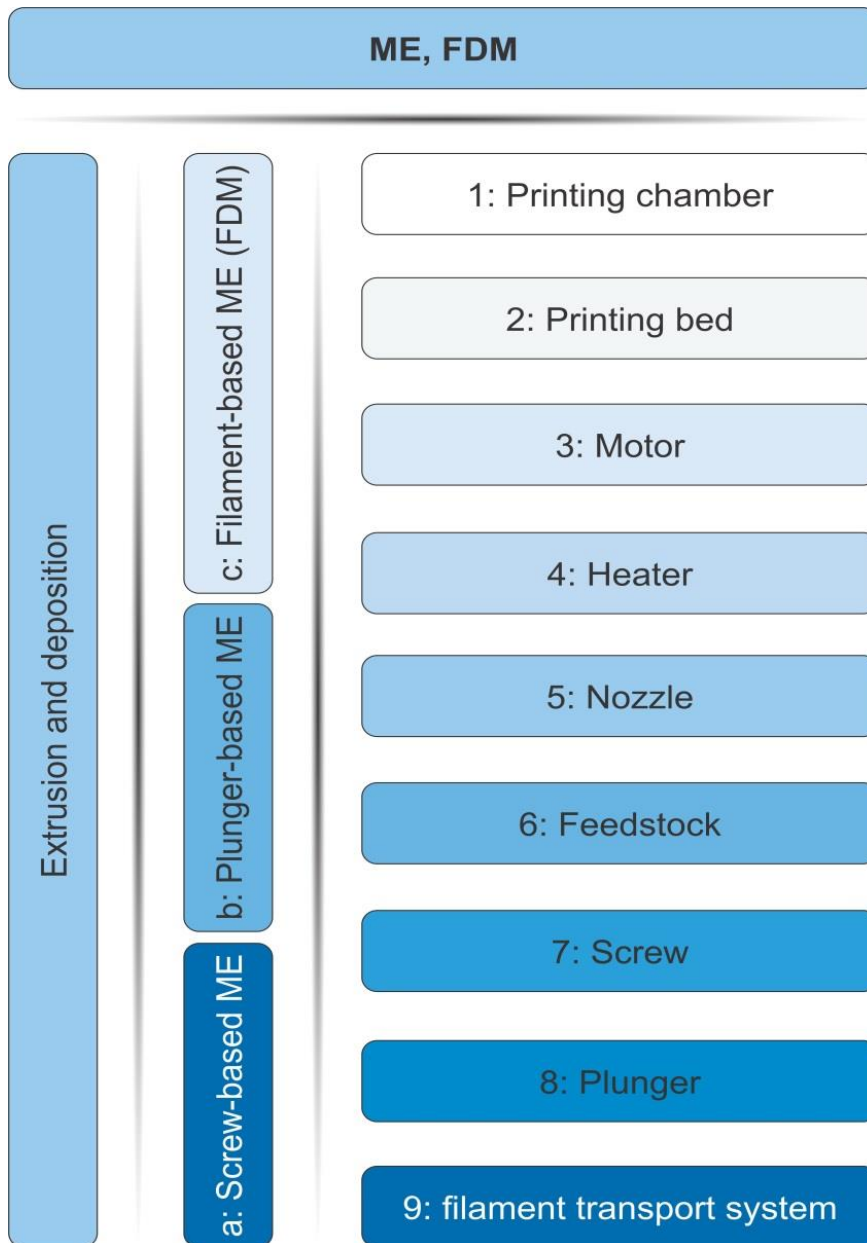


Figure 7: A tabular record of the components of ME and FDM

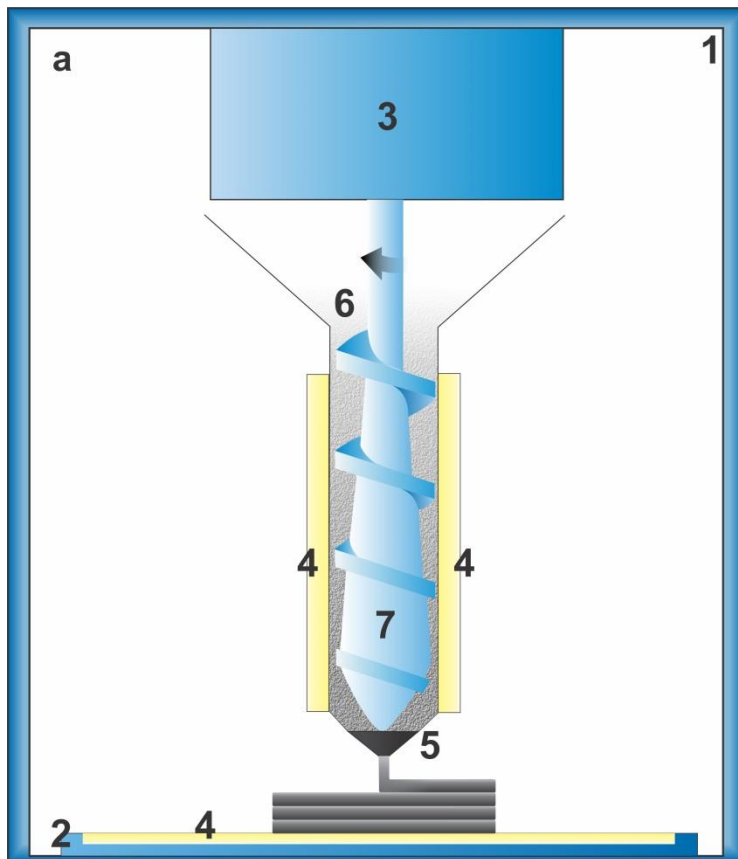


Figure 7a: Scheme of screw-based additive manufacturing material extrusion

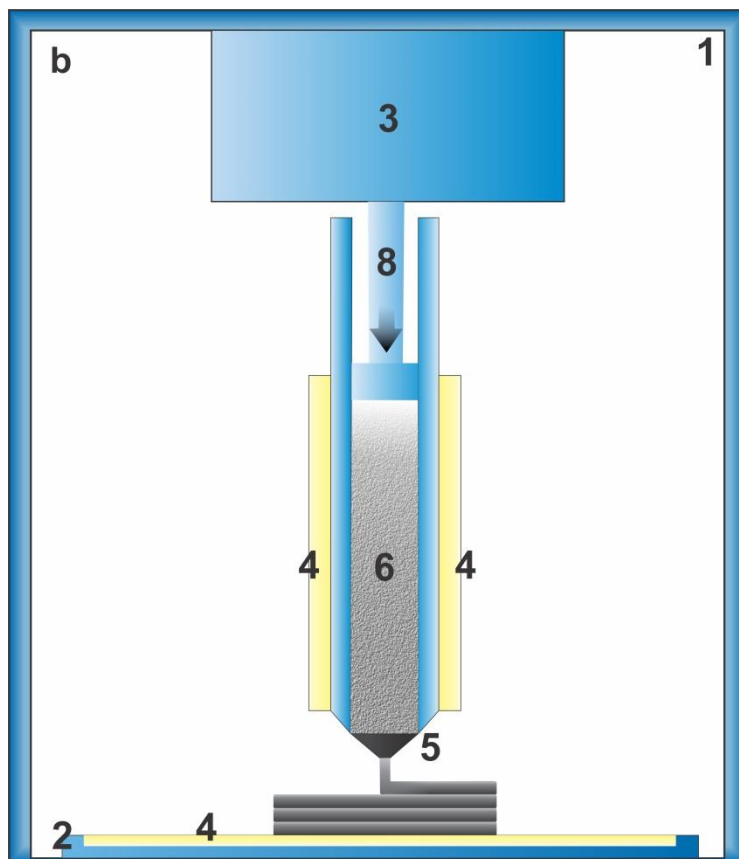


Figure 7b: Scheme of plunger-based additive manufacturing material extrusion

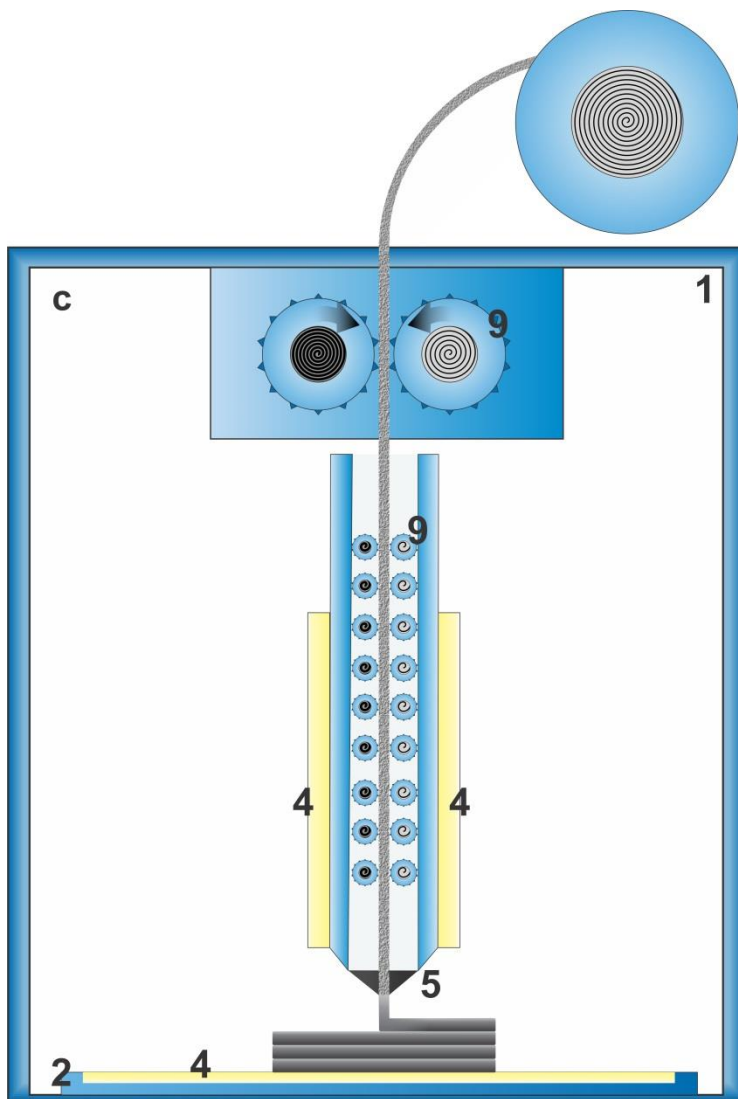


Figure 7c: Scheme of filament-based additive manufacturing material extrusion

Although ME can demonstrate lower energy consumption compared to traditional FDM manufacturing methods and processes, the specific materials used, setups used, and production rates must be considered to accurately estimate the overall energy requirements of each additive manufacturing method³³. A study analyzing the energy consumption and tensile strength of poly(methyl methacrylate) in ME highlighted the impact of various control settings on energy demands and mechanical properties of parts³⁴. Factors, such as extrusion temperature, build plate heating, printing speed, and motor/motion systems play a significant role in influencing energy consumption in ME processes³⁵. For example, in processes like FDM, a considerable portion of the energy is consumed by environmental heating during production³⁶.

To assess the environmental consequences of the innovative solutions arising from the AddCircles project, we plan to perform a comprehensive assessment of the AddCircles business cases using LCA. Therefore, an upcoming chapter 3.1 will delve into the relevant published scientific research related to AM and LCA. In Chapter 4, we will provide a fundamental overview of the principles of LCA.

3.1. Exploring Pertinent Scientific Research on Additive Manufacturing and Life Cycle Assessment

Amidst rapid advancements in various fields, emerging 3D printing processes and technologies underscore the importance of staying informed through scientific publications. Despite progress, challenges persist in the green additive manufacturing market, demanding scientific research and expertise in technical implementation, material selection, processing, AM process simulation, component simulation, life cycle analysis, and circular economy principles.

The rise of 3D printing techniques can also be attributed, in part, to increasing environmental awareness. Consequently, there is a burgeoning body of research and articles focused on LCA within the field.

AM has emerged as an important digital technology in improving production efficiencies. Therefore, the study *Towards Sustainable Production for Transition to Additive Manufacturing: A Case Study in the Manufacturing Industry*³⁷ investigated the impacts of redesigned products for transition to AM on sustainable production processes. In this study, an industrial-scale product was redesigned according to AM principles and manufactured using the FDM technique. The environmental impacts of the production methods were evaluated in terms of material consumption and carbon dioxide (CO₂) emissions using the LCA. Thus, according to LCA results, the use of a single type of material and production method for the redesigned product, as well as reducing the amount of material used by eliminating the fasteners, resulted in a 60.45% reduction in material consumption and 85.59% reduction in CO₂ emissions compared to conventional manufacturing. Although the production time in conventional manufacturing is shorter than FDM, the necessity of mold design and manufacture by pre-processing increased delivery time. Results show that the material unit costs for both manufacturing methods are very similar.

Also, a *Comparative LCA of Conventional Manufacturing vs. Additive Manufacturing: The Case of Injection Moulding for Recycled Polymers*³⁸ was created. The comparative analysis was performed between two manufacturing processes using black recycled Acrylonitrile Butadiene Styrene pellets to evaluate the potential environmental impacts between Injection Molding as CM (conventional manufacturing) and FDM 3D printer as AM. The LCA and the Unit Process Life Cycle Inventory methodology were adopted. The study primarily focused on

comparing the Global Warming Potential (GWP), cumulative energy demand, and mechanical tensile strength of parts produced using CM and AM. The GWP of both CM and AM systems was evaluated using two different methods, Impact 2002+ (Appendix No.1) and ReCiPe 2016 (Appendix No. 2). The GWP of AM parts was observed to vary with different infill percentages. The results indicated that increasing the infill percentage in AM parts led to an increase in cumulative energy demand. In contrast, the GWP of CM showed a reduction as batch sizes increased. When the batch size of CM increased from 7 to 14 parts the GWP decreased by up to 40%. Furthermore, there was a 56% reduction in GWP for a CM batch size of 50 parts compared to 14 parts. This reduction was attributed to decreased electric energy consumption per part as batch sizes increased. A positive correlation between these two factors was indicated.

Sustainability is the concept of satisfying the current needs of a society while safeguarding the needs of future generations. The objective of the study *Environmental life cycle assessment of an automobile component fabricated by additive and conventional manufacturing*³⁹, is to assess the environmental footprint of components manufactured using both AM and CM processes. This study specifically evaluates the rocker arm, an automotive component, in terms of its design, raw material usage, manufacturing processes, and their respective effects on the life cycle implications of AM and CM processes. The component is redesigned using topology optimization and Design for Additive Manufacturing (DfAM) approach. A cradle to gate LCA study of this component was conducted. The information for the life-cycle inventory is acquired from literature, relevant databases, and experimentation. The results indicate that the rocker arm manufactured by CM has less environmental damage of 14.53% compared to AM without topology optimization. AM with topology optimization has 21.31% less environmental damage compared to CM. The energy consumed for product manufacturing by Selective Laser Melting (SLM) process is the primary cause of environmental footprint. When optimization is included, the effect on the environment has reduced due to decrease in electricity and material consumption.

In the article *Environmental Assessment of Selective Laser Melting and Selective Laser Sintering*⁴⁰, Kellens et al. evaluated SLM and SLS manufacturing processes as capable of producing complex near-net shaped workpieces, offering opportunities for minimal waste and sustainable manufacturing. They recorded the consumption of electricity and used materials. Based on the performed LCA, the document describes the improvement potential for SLM/SLS machines with selective switching on-and-off of subsystems, the introduction of external cooling cycles, reduction of total machine time (in standby mode), and reduction of

manufacturing time (e.g. nesting efficiency, building height). When using the material, especially for SLS, a large impact on the environment was found due to the high amount of waste dust. In addition to measures that increase nesting efficiency (e.g. reducing building heights), more optimal recycling processes could reduce the amount of waste. Dotchev et al.⁴¹ provide a practical method for the collection and separation of no-sintered powder. To control the quality of the input material and more efficient use of fresh powder, they suggest the use of different rates according to the melt flow of the recycled powder. The most important is the well-thought-out choice of SLM/SLS equipment (e.g. the optimal size of the process chamber and vessel structure) because flexible process chambers and building containers enable the production of a wide variety of products (series) on the same machine tool, which limits the environmental impact created.

Nagarajan and Haapala⁴² determined how DMLS contributes to environmental impacts (material and energy losses) using energy analysis and large-scale life cycle production. The environmental impacts of DMLS ferrous metal powders were characterized by performing a thermodynamic analysis of sources and energy consumed and lost from cradle-to-gate. It is found that only 6% of the total process inputs in DMLS contribute to material processing while 94% is lost as bulk waste, heat, and labor. The results show that electricity consumption is a key contributor to the central process and related upstream processes. The systemic GWP impact for DMLS was determined to be 7.2 kg CO₂ eq. The overall ReCiPe 2008 indicator (a methodology, used for assessing and quantifying the environmental impacts of products and processes across multiple categories, such as human health, ecosystem quality, and resource depletion) shows that damage to human health is greater than damage to ecosystem quality (ecosystem quality = 84%, human health = 58%, resource depletion = 51%) and resource availability (ecosystem quality = 74%, human health = 29%, resource depletion = 19%) for DMLS procedure.

Certainly, while instances and research findings support the environmental benefits of additive manufacturing, it is important to acknowledge that this technology may not universally outperform traditional production methods in terms of eco-friendliness. In certain scenarios, conventional manufacturing methods may prove to be more sustainable, particularly when considering specific materials, production volumes, or operational efficiencies. Moreover, the life cycle analysis of products manufactured through additive processes may reveal hidden environmental costs, such as those associated with the disposal of unused or defective

materials, or the energy-intensive nature of certain additive techniques. Numerous examples and studies underscore the nuanced nature of this comparison as it is shown in the next cases. The study that compared AM data from LCA literature with conventional manufacturing data from the Granta EduPack database⁴³ has shown that metal AM generally exhibits higher carbon footprints per kg of material processed compared to CM processes like casting, extrusion, rolling, forging, and wire drawing. Factors influencing sustainability include part geometry, with AM being more advantageous for hollow shells or lattices, and aerospace industry use where lightweight parts can reduce impacts. Therefore, recommendations include using more relevant functional units for comparisons, such as standard reference parts representing typical applications in metal AM and CM. Comprehensive LCAs should consider impacts beyond processing energy, including consumables like argon for AM and tooling for CM, as well as embodied material impacts and end-of-life considerations. Also, the case of injection molding for recycled polymers study⁴⁴ indicates that the environmental impact of FDM is lower for batch sizes smaller than 14 parts. For larger batch sizes, however, conventional manufacturing may be more environmentally friendly. In some cases, AM may have higher human toxicity impacts compared to conventional manufacturing but it does not necessarily imply that AM is worse in all aspects⁴⁵. A review article on the LCA of AM processes⁴⁶ discusses the LCA of AM processes. However, it does not provide a definitive answer to whether AM is worse or better than conventional manufacturing. In summary, the search results do not always conclusively demonstrate that AM has a worse or better environmental impact than conventional manufacturing across all scenarios.

Research of various aspects and tools of AM, including *EcoPrintAnalyzer: Assessing Sustainability in Material Extrusion Additive Manufacturing for Informed Decision-Making*⁴⁷, highlights the potential to improve sustainability by raising awareness of its environmental benefits. Key drivers are design optimization and increased awareness, allowing engineers to create more efficient designs. The EcoPrintAnalyzer tool, a plugin for UltiMaker Cura, helps assess the environmental impact of AM by providing data on carbon footprint and energy use. It promotes informed decisions on materials and designs, reducing waste and improving energy efficiency. A case study using the 3DBenchy model demonstrates the tool's effectiveness and ease of use in optimizing AM processes for sustainability.

Since substantial energy demand is systematically addressed also as one of the main reasons for ecological damage in FFF, mitigation strategies are often based on reducing the printing time (for example, adopting thicker layers) or the embodied energy per part (e.g., by nesting,

which means by printing multiple parts in the same job). The adoption of electricity from renewable resources is also expected to boost the sustainability of distributed manufacturing through FFF⁴⁸.

A relevant scientific article discussing material extrusion additive manufacturing (MEX) in lightweight structures and its environmental impact through LCA is titled *Material extrusion additive manufacturing of novel lightweight collinear stayed polymer lattices*⁴⁹.

Further, study **Comparative Life Cycle Assessment of SLS and mFFF Additive Manufacturing Techniques for the Production of a Metal Specimen**⁵⁰, presents a detailed LCA comparing SLS with modified Fused Filament Fabrication (mFFF). It highlights that SLS has significantly lower energy consumption and environmental impact compared to mFFF, making it a more sustainable option for producing metal specimens. The assessment covers various impact categories, including global warming potential and resource depletion.

In the literature, comparison of LCA reports is a challenge due to differences in data in research articles and LCA methodologies. Each LCA may not consistently include the same data or present it uniformly. Furthermore, the outcome of an LCA often depends on the defined value chain for a particular product^{51,52,53} (see Figure 8).

So, we should also mention that additive manufacturing has transformed traditional supply chains by moving from a push to a pull system. You can read about what this form of supply chains entails in the article *Implications of Additive Manufacturing on Supply Chain Management*⁵⁴, which explores the risks, opportunities and strategies companies are using to adapt. Key changes include improved time, quality, speed and environmental impact, leading to better resource management, lower costs, shorter lead times and increased customer satisfaction through customization. The flexibility and efficiency gained are in line with the goals of sustainable development and indicate future trends in the industry⁵⁵.

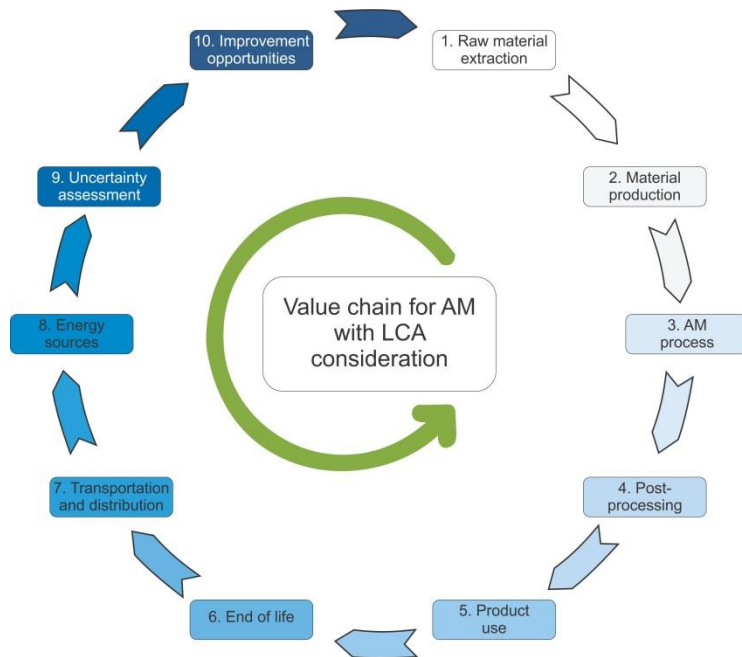


Figure 8: Life cycle assessment value chain for additive manufacturing

Here is a simplified general value chain for AM with LCA considerations:

Ad.1: Assessment of the impact of material extraction on the environment (energy consumption, emissions, etc.).

Ad. 2: Processing raw materials into forms for printing (filaments, powders, etc.). Assessment of energy consumption, emissions, and waste during production.

Ad. 3: Consideration of energy consumption, emissions, and waste generated during printing.

Ad. 4: Analysis of the environmental impacts of post-processing steps, e.g. removing the support structure, cleaning and finishing the printed object.

Ad. 5: Estimation of energy consumption during the life of the product. Consideration of factors, such as maintenance, repairs, and energy efficiency.

Ad. 6: Assessment of disposal options (recycling, disposal, etc.) at the end of the useful life. Quantifying the impact of disposal on the environment.

Ad. 7: Consideration of energy consumption and emissions associated with the transportation and distribution of raw materials, printed items, and finished products.

Ad. 8: Overview of all energy sources used throughout their life cycle (renewable or non-renewable). Normalization and assessment of environmental impact based on consideration of all energy sources.

Ad. 9: Uncertainty Assessment in data and assumptions to understand confidence levels in LCA results.

Ad. 10: Identification areas for optimization (e.g., material selection, energy-efficient printing, waste reduction) and exploration of research avenues for better LCA models and data.

Although a low material waste using AM are environmentally friendly, its environmental impacts must be assessed using LCA. The adoption of AM processes must also be assessed economically in order to ensure that they are economically viable. In the study *Life cycle assessment and economics of additive manufacturing processes*⁵⁶, existing studies on LCA and the economic assessment of AM processes are reviewed. The performance of AM processes was also compared with traditional manufacturing technologies and, the circumstances in which AM is more environmentally friendly and inexpensive compared to conventional manufacturing processes. AM practitioners can use this review to choose a more economical and ecological manufacturing process for their products and minimize emissions and production costs.

In the following, we also provide a summary of the report *Ex-ante ecological performance of additive manufacturing technologies*⁵⁷, which was designed in 2023 by Wood K plus (Dr Franziska Hesser, Julia Velkovski) and Fraunhofer Austria (Dr Arko Steinwender). In order to better exploit the ecological potential of AM production technologies, their aim was to systematically investigate the environmental aspects and potential impacts during development for industrial use, and to derive recommendations for action:

The aim of the study was to use a bottom-up approach (from a technology or application perspective) and a top-down approach (from a life cycle assessment perspective) to find out in which areas of AM ecological advantages can be localised and how these are expressed quantitatively. An additional aim was to find out how these ecological benefits can be utilised to support the transformation towards a more sustainable production and economy.

First, the study identified the initial advantages of AM in terms of its environmental impact, with these being low raw material requirements, flexible product design, decentralisation and the associated reduction in transport, a lower number of individual parts, automation, repair options through AM and lightweight construction. On the other hand, the energy consumption and the use of materials were also identified as critical hotspots. The major energy consumers

are raw material extraction, material production and the printing process. Energy consumption depends on the application patterns, equipment utilisation, the material selected, the AM process and the complexity of the component. However, savings can be made by optimising the arrangement of components, optimising the production process and suitable process and component design. While the lack of recyclability is criticised when it comes to the use of materials, the variety and efficiency of materials is seen as an advantage.

Second, the study also identified challenges and potential of AM in comparison to conventional processes. These challenges include increasing the efficiency of powder use, increasing the efficiency of the manufacturing process, the high energy consumption in production, the low surface quality, the high energy consumption in powder production, the recycling of waste and the environmentally friendly use for larger quantities. The identified potential include material savings, lightweight construction, better environmental performance at high capacity utilisation, the possibility of using hybrid processes, high efficiency for small series, the possibility of environmentally friendly production of geometrically complex parts and flexible design, the reduction of waste, the possibility of tool-free production, energy savings over the entire product life cycle and the possibility of individualised large-scale production of user-defined components.

In term of the LCA, the authors of the study noted that the comparison of existing environmental data represents a major challenge, as the studies select different functional units and system boundaries. Furthermore, the data usually relate to a specific application without taking into account the possibility of transferability to other applications. Standardised methods and models are therefore required by the scientific community.

The authors of the study also conducted a series of workshop-based multi-perspective expert panels, where they identified challenges and the impact on AM in collaboration with relevant stakeholders from industry. Based on these interviews, energy efficiency, resource conservation and waste reduction, recycling and circular economy, environmental protection by reducing the use of hazardous substances, CO₂ savings and extending the service life of products were identified as the most relevant challenges. AM tends to have a favourable effect on resource conservation, CO₂ savings and extending the service life of products. In general, AM tends to have an inhibiting effect on energy efficiency, recycling and the circular economy.

Finally, the study proposed recommendations for action for ecological production through AM is based on literature review, interviews with experts from industry and LCA. The

recommendations for action were divided into three groups: industry, research and public. For industry, the study recommended an application of an ecological design based on the intelligent use and manufacture of products, extending the service life of products and recycling materials, as well as use of bio-based materials and secondary materials, utilisation of waste materials both within and beyond AM sector, optimisation and automatization of processes and strengthening of cross-company exchange of experience. For research and development, the authors recommend development of solutions to facilitate ecological assessment, systematic processing of various utilisation concepts and applications, increasing efficiency in material and production and development of new or enhanced simulation tools based on eco-design principles. Finally, for politics and public sector study recommended increase in the research funding and training programmes, incentives to consider life cycles at the end product level, exchange of information and development of joint strategies for greener production, increased dialogue with the AM sector, creating more infrastructure for recycling and incentivising the use of secondary materials, create standards for quality requirements and criteria for various AM applications and industries, and create creating incentives in other industries to break up traditional designs.

To improve our understanding of the environmental impacts, it becomes imperative to carry out thorough LCA studies for each mentioned phase of the AM process and to consider each case separately.

4 Best practice examples in additive manufacturing and recommendations for SMEs

Additive manufacturing (AM) has developed rapidly and offers various opportunities for innovation and efficiency. For small and medium-sized enterprises (SMEs), implementing AM can significantly increase productivity and product quality. After reviewing the literature, we find that AM has been successfully implemented in various areas, e.g., for parts of the automotive industry, medical and sports equipment, various complex industrial products, etc. In the following, we present some successful stories of AM implementation which also found their place in the market and end-use.

4.1 Best Practice Examples in Additive Manufacturing

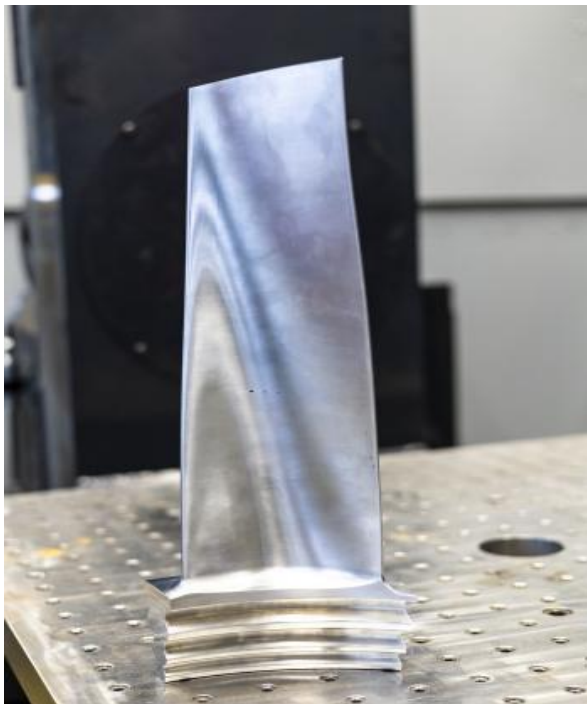
Company GE Aviation has been 3D printing fuel nozzles for jet engines busily since 2015, reaching a total of 30,000 3D printed fuel nozzles at its Auburn, Alabama, additive manufacturing center in 2018⁵⁸. GE used additive manufacturing to produce a single-piece fuel nozzle that was previously made from 20 different parts. This improved performance, reduced weight by 25%, and increased durability.



Source: LEAP fuel nozzle <https://3dprint.com/284243/ge-aviation-announces-100000th-3d-printed-fuel-nozzle-shipped-from-auburn-plant/>

Also, a relevant scientific article discussing the use of additive manufacturing for jet engine fuel nozzles is titled "Simulation-Based Analysis of Additive Manufacturing Systems for Fuel Nozzles"⁵⁹. This study focuses on the production of gas turbine fuel nozzles using additive manufacturing technology. It employs a discrete-event modeling and simulation approach to evaluate manufacturing performance, considering various production parameters like resource utilization and throughput time. The research emphasizes the advancements in additive manufacturing, particularly in the context of the new GE fuel nozzle designed for the CFM International LEAP engine which is significantly lighter and more efficient than traditional designs.

Oak Ridge National Laboratory (ORNL), in collaboration with Siemens Technology, has used metal 3D printing to create large, rotating steam turbine blades for power plants (Gas turbine blades)⁶⁰. This feat, achieved through wire arc additive manufacturing (WAAM), marks a significant milestone in the production of large-scale metal parts, particularly for the energy segment. Siemens produced gas turbine blades using additive manufacturing, allowing for complex internal cooling channels that improved efficiency and performance.



Contoured steam turbine blades require a very precise shape, with contoured curves that narrow toward the tip. Wire arc 3D printing was not used previously to make a rotating component of this scale. Credit: Carlos Jones/ORNL

Source: <https://3dprint.com/305846/siemens-and-ornl-3d-print-25-pound-turbine-blade-with-waam/>

Key challenges in manufacturing turbine blades with AM include optimizing additive manufacturing process parameters, post-processing printed parts, and ensuring that mechanical

properties meet the stringent requirements for turbine blades. Many corporations and research teams are already dealing with these kinds of challenges which is why quite a lot of literature on this topic can also be found in the scientific literature^{61, 62}.

Ayush Sinha et al studied the processing methods of 3D-printed aero-turbine blades and presented the experimental results of testing these blades on a 13-megawatt industrial gas turbine type SGT-400. They found the ability of 3D-printed blades to withstand extreme operating conditions⁶³.

Some of the most complex manufacturing routinely performed is devoted to producing orthopedic devices for implantation. To produce implants that are not only geometrically accurate but are made of material that mimics the porous structure of the cancellous bone, such as in spinal applications, Stryker did not only develop a proprietary material process, but proprietary hardware and software to additively make the components⁶⁴. Stryker has been working in the AM field for more than 10 years and says that the process they have developed for making surgical implants “enables the creation of previously difficult or impossible product designs.” One of the fundamental differences developed at Stryker for its additive application is what it is called “Titanium In-Growth Technology.” The titanium alloy produces parts that are strong, stiff, and, importantly, biocompatible. Stryker uses additive manufacturing to create customized, patient-specific implants with complex geometries that promote better bone integration.



The Stryker Monterey AL Interbody System is produced with the company's proprietary powder bed fusion system called "AMagine". Stryker produces implants that have a porous matrix that mimics cancellous bone. During a surgical procedure, the surgeon inserts the cage which is produced with additive that holds the cam locks (the gold elements). The three screws are inserted through the cage and into the vertebral bodies. Then, the cam locks are rotated to secure it in place. Photo Credit: Stryker

Source: <https://www.additivemanufacturing.media/articles/stryker-using-additive-for-implants>

The review article Three-dimensional Printing in Orthopaedic Surgery highlights the transformative role of 3D printing in orthopedic surgery, emphasizing its ability to create patient-specific implants and instrumentation. It discusses the advantages of 3D printing, including customization, efficiency in production, and the benefits of personalized implants that enhance osseointegration and reduce surgical time. The article also explores the future potential of 3D bioprinting in bone and cartilage restoration and discusses the limitations, including the need for advanced modeling software and regulatory guidance, which could hinder broader application in clinical settings^{65, 66}.

Several manufacturers, including Adidas, have been interested in using 3D printing technology in their shoe designs, knowing it can produce complex shapes using different material mixtures. What Adidas wanted to achieve with 3D printing was to make proper use of the technology's potential for making incredibly intricate lattice structures tailored for optimized cushioning and performance. In their partnership with Carbon, the design of the Futurecraft 3D printed midsole is based on optimized data (pressure points from wearing the shoes) collected from athletes around the world. This resulted in the midsole's complex lattice structure being denser, stiffer, or softer in certain areas. The midsole was 3D printed on [Carbon's M2 3D printer](#) (Carbon's Digital Light Synthesis technology) out of curable UV resin and polyurethane. This exact material mixture also absorbs more energy than a standard midsole which should enhance running performance. The midsoles are also quite smooth, which makes them easy to clean.



Source: <https://all3dp.com/2/adidas-3d-printed-shoes/>

Other research on complex mesh structures for (sports) shoes has also gained much attention due to advances in AM. For example, in the *Efficacy of Auxetic Lattice Structured Shoe Sole*⁶⁷ study, the effect of auxetic structured shoe soles on plantar biomechanics and comfort is researched. It focuses on three-dimensional reversible auxetic lattice structures that can optimize the distribution of foot pressure and increase comfort. The research compares

different mesh structures created by 3D printing and reveals that auxetic designs exhibit unique mechanical properties beneficial to footwear. A similar scientific article on the design of shoe soles using lattice structures fabricated by AM discusses the customization potential of shoe soles using various lattice topologies, including Diamond, Grid, X shape, and Vintiles⁶⁸. The study highlights how different lattice designs can influence the mechanical performance of shoe soles. AM technology is very close and connected with digitalization. The customized Porous Lattice Sole can have a data-driven design, which was shown with the research of a method for generating a fully customized porous shoe sole using a data-driven design optimization algorithm. The approach allows for adjustments in strut diameters within the lattice structure to minimize peak plantar pressure, demonstrating the potential for tailored footwear solutions that can prevent or treat conditions like diabetic ulcers⁶⁹.

The breakthrough information is related to the fact that already in the medical, dental, food, and pharmaceutical industries, FDA approvals are granted to companies for the use of additive manufacturing. One such company is Align Technology. Cubicure (owned by Align Technology) holds patents related to hot lithography technology and uses high-precision 3D printing processes based on a heat-and-coat mechanism to produce strong, temperature-resistant polymers from highly viscous resins. In December 2023, Align received FDA clearance for its first direct 3D-printed orthodontic appliance, the Invisalign Palatal Expander System, which addresses skeletal and dental expansion in younger patients⁷⁰. Align Technology uses 3D printing to produce custom-fit Invisalign clear aligners for orthodontic treatment, revolutionizing the dental industry with personalized products.



Less painful than traditional palatal expanders.
Clinically proven to be safe and effective.
A revolutionary new design with **no metal screw**.

Source:

<https://www.invisalign.com/palatal-expander>

Additive manufacturing technology has strongly penetrated various industries and now 3D printed products are appearing more and more on the market. Companies and industries adapt AM to their specific needs. As can be seen in the literature, they often connect with manufacturers of 3D printing equipment, IT designers, and other professionals, with the desire

to improve AM processes in ways that increase the benefit/efficiency/simplify the production of demanding products for their products and production processes.

Companies that have already integrated AM into their processes have also been publishing the results, often along with guidelines that can be useful for SMEs. In the following, we collected and formulated some recommendations that often appear in the literature.

3.2 Recommendations for SMEs

In the following composition, we have described some tips for SMEs about hybrid (AM-conventional) production, but they should be aware that although hybrid production could increase competitiveness in the long term, SMEs should carefully consider the financial, operational costs of training and other issues.

Currently, the cost of new AM equipment, especially in advanced industries (e.g. aerospace, healthcare), is highly specialized and expensive. While hybrid manufacturing can streamline processes, purchasing new AM and conventional machinery requires significant upfront capital investment. The return on investment (ROI) of hybrid production may take longer to materialize. In addition, the cost of training a skilled workforce to operate and maintain the new machines will be required. For starters, alternative solutions for SMEs to reduce these costs may be to outsource/rent or adopt modular upgrades to existing conventional machines that can sometimes be retrofitted to include basic AM capabilities without complete replacement.

- Start with prototyping to reduce the time and cost of new product development. For this purpose, it would be a good idea to invest in desktop 3D printers for creating prototypes in the company, which allows rapid iteration and validation of the design.

For example:

<https://formlabs.com/applications/rapid-prototyping/>

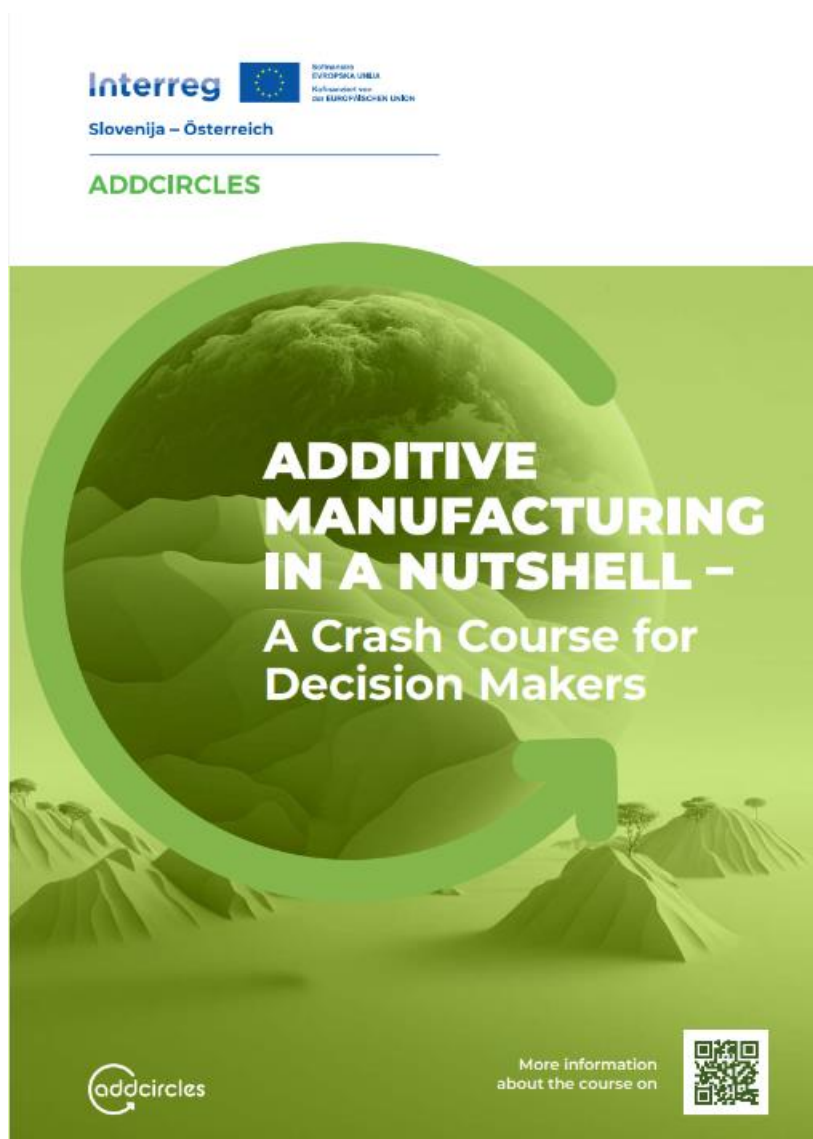
<https://www.3dsourced.com/rankings/best-3d-printer-for-small-business/>

- Take advantage of customization and offer unique products tailored to the needs of individual customers. By researching the market and market niches where customization adds significant value (e.g. in medical devices and sports products), important finesse can be created/created/processed. It can create an advantage over the competition.
- Adopt hybrid manufacturing by combining traditional and additive manufacturing to optimize production. Integrate 3D printing to produce complex or small components while using traditional methods for simpler, higher-volume parts. Research has shown that the effectiveness and justification of the production process (AM or traditional) depends on the complexity of the product and mass production (number of manufactured pieces).
- Focus on material innovation to improve product functionality and performance. Research and use advanced materials, such as high-performance polymers, metals, and composites suitable for additive manufacturing. The development of new materials will always be one of the variables that will enable the improvement of both 3D printing (process) and the improvement of the properties of the 3D printed product.
- Improve supply chain flexibility to reduce reliance on external suppliers and shorten lead times. Use additive manufacturing to produce custom spare parts and tools on demand, reducing inventory costs and increasing operational flexibility⁷¹.
- Train and upgrade the workforce to ensure proficiency in the latest AM technologies and methodologies. Invest in training programs and workshops to educate employees on Design for Additive Manufacturing (DfAM) principles and how AM machines work.

For training and upgrading in the topic of AM technologies, several courses and programs are available in 2024:

- a) MIT xPRO's, Additive Manufacturing for Innovative Design and Production. This professional certificate program provides a comprehensive understanding of AM technologies, focusing on innovative design and production methods. It includes practical exercises, case studies, and interaction with industry experts (<https://learn-xpro.mit.edu/additive-manufacturing>).
- b) In Europe, Italy, Rome: 4th International Conference on 3D Printing and Additive Technologies (iC3DPAM-2025). February 20-22, 2025. Conferences will provide a forum for researchers working on all aspects of 3D printing and AM.
- c) Europe, France, Paris: Inovine Meetings LLC provide an amazing chance to communicate with world-class scientists, Astronauts and experts at Global Summit on 3D Printing during June 04-05, 2025 at Paris, France. This conference aims to showcase the latest advancements, trends, and applications in the field, providing attendees with a comprehensive understanding of the potential and impact of 3D Printing.
- d) Europe, Austria, Vienna: 7th M3d+it CONFERENCE, taking place in VIENNA, Austria, on 29-30 NOVEMBER 2024. At this conference, we will tackle not only scientific challenges, such as cutting-edge 3D-printable materials for implants, advancements in micro/nano 3D-printing, and novel medical device design methods, but also practical issues like regulatory hurdles and cost reimbursement for implementing 3D printing at the point of care. The event will include international sessions featuring representatives from national 3D printing networks across Europe, as well as insights from ongoing European research projects. Additionally, this conference will host the annual meeting of the “European Special Interest Group for 3D Technologies in Hospitals”.
- e) UC San Diego's, Additive Manufacturing Technologies. This course covers a range of 3D printing technologies, such as Fused Deposition Modeling (FDM), Vat Polymerization, Binder Jetting, and Powder Bed Fusion. It emphasizes the integration of AM in Industry 4.0 and includes training on supporting software, materials, and post-processing (<https://extendedstudies.ucsd.edu/courses-and-programs/additive-manufacturing-technologies>).

- f) University of Illinois at Urbana-Champaign's, 3D Printing and Additive Manufacturing Specialization. This specialization consists of five courses that delve into the hardware and software aspects of 3D printing. It includes hands-on projects, enabling learners to design, make, and share 3D-printed objects. (<https://www.coursera.org/specializations/3d-printing-additive-manufacturing>).
- g) Also, the ADDCIRCLES Interreg SLO-AUT project offers various workshops and presentations that spread knowledge about AM technology.



- Work with AM service providers to access advanced technologies without major capital investment. Work with specialized AM service bureaus for high-end manufacturing

needs or researching new materials and techniques. Collaboration with digitization and AI experts has also proven to be good.

- Establish testing and quality assurance protocols specific to additive manufacturing processes, including materials testing and inspection of printed parts. Control and testing to ensure consistent and reliable product quality is critical when establishing new process technologies.
- Before establishing new processes, it is recommended to explore new business models to create new revenue streams and achieve competitive differentiation. This opens up new ideas and a view of the current state of good practices. Consider on-demand manufacturing, digital inventory, and subscription services for custom products.

https://link.springer.com/chapter/10.1007/978-981-19-7071-9_5

<https://www.mckinsey.com/capabilities/operations/our-insights/the-mainstreaming-of-additive-manufacturing>

- Last but not least, today a sustainable approach to reduce environmental impact and meet the growing demand for sustainable practices and products is essential. Use AM to reduce material waste, produce lightweight components, and explore biodegradable or recyclable materials⁷²⁷³.
- Do not forget that innovations are permanent parameters in the production of any product because, with them, we can always improve competitiveness. To illustrate the importance of innovation in enhancing competitiveness, consider the S-Curve pattern of innovation, which shows how industries, products, or business models evolve over time. Continued innovation is crucial for maintaining competitiveness in the market (Future Business Tech; Source: <https://www.futurebusinesstech.com/blog/the-s-curve-pattern-of-innovation-a-full-analysis>).

5. Conclusions

One of the key advantages of AM in the context of Industry 4.0 is its ability to enable agile and flexible production processes. Traditional manufacturing often relies on mass production methods that involve extensive setups and tooling, leading to higher costs and longer lead times. In contrast, additive manufacturing enables the creation of complex, customized, and small-batch production runs with reduced set-up times, offering unparalleled flexibility to meet the demands of dynamic markets.

Most often 3D printing is related to environmental concerns and LCA with (i) reducing material waste because 3D printing, especially when using techniques like material extrusion or powder bed fusion, can be more efficient because objects are built layer by layer; (ii) 3D printing can be more energy-efficient for certain applications when it consumes low energy and only when needed to melt or fuse the material. Traditional subtractive manufacturing processes, like CNC machining, may require more energy to remove excess material; (iii) local and on-demand production, which is particularly relevant for low-volume production; (iv) with lightweighting and optimization of 3D printing enables the creation of complex, lightweight structures that would be difficult or impossible to manufacture using traditional methods. This can result in reduced material usage and transportation costs; (v) some 3D printing processes, like selective laser melting for metal parts, allow for the use of recycled materials.

All mentioned above aligns with the principles of the circular economy where products are designed with sustainability in mind.

6. Additional Information

Recently, sustainability has been top of mind for companies and consumers. Therefore AM is gaining prominence as a sustainable alternative to traditional manufacturing in certain situations, such as rapid prototyping, spare parts, and mass customization.

However, are we fully aware of the impact AM can have on the environment, and how sustainable it is?

Within the framework of the AddCircles project, we are in the process of developing a comprehensive booklet, inclusive of a final report. This report will delve, based on research, into the LCA and LCCA of three innovative AM business cases.

6.1. Appendix 1

Section 5.1 provides further clarification on specific terms and phrases for enhancing comprehension of the content and a more accessible understanding of the sustainable approach.

No. 1: Impact 2002+: The new IMPACT 2002+ life cycle impact assessment methodology proposes a feasible implementation of a combined midpoint/damage approach, linking all types of life cycle inventory results (elementary flows and other interventions) via 14 midpoint categories to four damage categories. For IMPACT 2002+, new concepts and methods have been developed, especially for the comparative assessment of human toxicity and ecotoxicity. Human Damage Factors are calculated for carcinogens and non-carcinogens, employing intake fractions, best estimates of dose-response slope factors, as well as severities. The transfer of contaminants into human food is no longer based on consumption surveys but on accounts for agricultural and livestock production levels. Indoor and outdoor air emissions can be compared and the intermittent character of rainfall is considered. Both human toxicity and ecotoxicity effect factors are based on mean responses rather than on conservative assumptions. Other midpoint categories are adapted from the existing characterizing methods (Eco-indicator 99 and CML 2002). All midpoint scores are expressed in units of a reference substance and related to the four damage categories: human health, ecosystem quality, climate change, and resources. Normalization can be performed either at the midpoint or at the damage level. The IMPACT 2002+ method presently provides characterization factors for almost 1500 different LCI results, which can be downloaded at <http://www.epfl.ch/impact>⁷⁴.

No. 2: ReCiPe 2016: ReCiPe 2016 is an improved version of the ReCiPe method, originally introduced in 2008. Developed by the Dutch National Institute for Public Health and the Environment (RIVM), Radboud University Nijmegen, Norwegian University of Science and Technology, and PRé Sustainability, ReCiPe 2016 aims to translate life cycle inventory results into a limited number of indicator scores representing environmental impact categories. The method includes 18 midpoint indicators and 3 endpoint indicators, covering human health, ecosystem quality, and resource scarcity as areas of protection. ReCiPe 2016 updates previous versions by incorporating new data and research, providing characterization factors for various impact categories, and offering country-specific factors where applicable⁷⁵.

No. 3: Global Warming Potential (GWP) is crucial for climate science and policy-making, allowing scientists and decision-makers to understand the cumulative contributions of various GHGs to global warming.

GWP is a metric used to compare the effectiveness of different greenhouse gases in contributing to global warming over a specified time horizon relative to carbon dioxide (CO₂) which has a GWP of 1. GWP considers two primary characteristics of GHGs: (i) their capacity to absorb infrared radiation (referred to as radiative efficiency) and (ii) their residence time in the atmosphere (atmospheric lifetime).

A higher GWP indicates that gas causes more global warming per unit mass compared to CO₂ over the selected period. For example, methane has a GWP of around 25 times that of CO₂ over 100 years while nitrous oxide has a GWP of roughly 273 times that of CO₂⁷⁶.

In the literature, we most often found the following several other techniques (expressions) for environmental impact assessment besides those mentioned here which are techniques that vary in their scope, methodology, and focus, for example:

No. 4: Ecological Footprint Analysis assesses the human demand for nature by comparing human consumption of natural resources with Earth's ecological capacity to regenerate them.

No. 5: Carbon Footprint Analysis focuses specifically on measuring and reducing greenhouse gas emissions associated with a product, service, or activity.

No. 6: Material Flow Analysis (MFA) tracks the flows and stocks of materials within a system to understand resource use, waste generation, and environmental impacts.

No. 7: Water Footprint Assessment evaluates the amount of water used directly and indirectly by a product or process, considering both consumption and pollution aspects.

6.2. Appendix 2

Commonly used terms for AM that can be found in Global Literature:

- Rapid Prototyping (RP)
- Direct CAD Manufacturing
- Desktop Manufacturing
- Instant Manufacturing
- CAD Oriented Manufacturing
- Layer Manufacturing
- Material Deposit Manufacturing
- Material Addition Manufacturing
- Solid Freeforming

Hot news at the end of the report

USA: At the moment, the high-profile news in the field of additive technology is NASA's RAMPT (Rapid Analysis and Manufacturing Propulsion Technology) project in the use of large-scale additive manufacturing to produce complex, high-performance rocket components. The project aims to reduce costs and production times for essential parts such as the RS-25 engine, a critical component in deep space exploration missions. Equally, AM is critical to reducing time-to-market and improving efficiency in semiconductor manufacturing, where it is increasingly integrated especially in the creation of complex, high-density components such as solid-state memory and high-performance processors.

It is in this area that the most significant recent development in AM regulation revolves around the US Federal Aviation Administration (FAA), which has launched a comprehensive eight-year plan focused on integrating AM into the aerospace industry. This plan is critical as it sets out a strategic approach to ensure safety and consistency in the production of parts using AM technologies. It covers key areas such as parts certification, machine maintenance and research and development, with significant input from NASA, the US military and other key industry players.

Additionally, the broader regulatory arena has seen an increase in attention from other government agencies, including the General Services Administration (GSA), which is actively working with AM providers to expand federal capabilities. This initiative indicates a growing government effort to standardize and regulate AM technologies in various sectors (US General Services Administration). The development of AM regulation is becoming more and more involved in critical industries, especially those where safety and reliability are paramount.

EU: The regulatory landscape for AM in the European Union is evolving, particularly in the context of medical devices and pharmaceuticals. The introduction of the EU Medical Device Regulation (MDR) in 2017, which came into effect in May 2021, has significantly impacted how 3D printed medical devices are classified and regulated. The MDR has redefined what constitutes a custom-made medical device. Under the new regulations, a custom-made product is one that has specific design characteristics tailored for the sole use of a particular patient, based on a written prescription from a qualified medical professional. However, the MDR excludes mass-produced devices that are merely adapted for individual patients from being classified as custom-made^{77, 78}.

7. Literature

In the Literature section, we have curated a selection of scientific articles and open-access publications available on the internet, each directly relevant to a specific topic. Feel free to explore these resources for in-depth insights into the particulars that pique your interest.

¹ SIST EN ISO/ASTM 52900:2022 Additive manufacturing – General principles – Fundamentals and vocabulary (ISO/ASTM 52900:2021) = Aditivna proizvodnja – Splošna načela – Osnove in terminologija (ISO/ASTM 52900:2021)

² Tofail, S.A.M., Koumoulos, E.P., Bandyopadhyay, A., Bose, S., Donoghue, L.O., Charitidis, C.: Additive manufacturing: scientific and technological challenges, market uptake and opportunities. *Mater. Today* 21, 22–37 (2018). <https://doi.org/10.1016/j.mattod.2017.07.001>

³ Heng Deng, Jian Lin, Chapter 8 – 4D Printing: 3D Printing of Responsive and Programmable Materials,

Editor(s): Lijie Grace Zhang, John P. Fisher, Kam W. Leong, 3D Bioprinting and Nanotechnology in Tissue Engineering and Regenerative Medicine (Second Edition), Academic Press, 2022, Pages 213-237, <https://doi.org/10.1016/B978-0-12-824552-1.00012-8>.

⁴ About Additive Manufacturing. <https://www.lboro.ac.uk/research/amrg/about/materials/>. (Accessed 23.1.2024)

⁵ Ans Al Rashid, Muammer Koç, Additive manufacturing for sustainability and circular economy: needs, challenges, and opportunities for 3D printing of recycled polymeric waste, *Materials Today Sustainability*, Volume 24, 2023, 100529, <https://doi.org/10.1016/j.mtsust.2023.100529>.

- ⁶ Matthew A. Olawumi, Bankole I. Oladapo, Omolayo M. Ikumapayi, John O. Akinyoola, Waste to wonder to explore possibilities with recycled materials in 3D printing, *Science of The Total Environment*, Volume 905, 2023, 167109, <https://doi.org/10.1016/j.scitotenv.2023.167109>.
- ⁷ Ruiz, L.E.; Pinho, A.C.; Resende, D.N. 3D Printing as a Disruptive Technology for the Circular Economy of Plastic Components of End-of-Life Vehicles: A Systematic Review. *Sustainability* 2022, 14, 13256. <https://doi.org/10.3390/su142013256>
- ⁸ Hayley Everett, CIRCULAR ECONOMY 3D PRINTING: OPPORTUNITIES TO IMPROVE SUSTAINABILITY IN AM, 2021 (Accessed 23.1.2024)
- ⁹ John Duffy, PowderCleanse: Solving powder-bed fusion's waste problem. 2023 (Assessed on 10.9.2024)
- ¹⁰ HE, Xing, et al. Powder recycling effects on porosity development and mechanical properties of Hastelloy X alloy during laser powder bed fusion process. *Additive Manufacturing*, 2022, 55: 102840.
- ¹¹ Prima Additive S.r.l., Material Reuse in Additive Manufacturing: Prima Additive's Sustainable Approach. 2024 (Assessed on 10.9.2024)
- ¹² Kassab, A.; Al Nabhani, D.; Mohanty, P.; Pannier, C.; Ayoub, G.Y. Advancing Plastic Recycling: Challenges and Opportunities in the Integration of 3D Printing and Distributed Recycling for a Circular Economy. *Polymers* 2023, 15, 3881. <https://doi.org/10.3390/polym15193881>
- ¹³ Ans Al Rashid, Muammer Koç. Additive manufacturing for sustainability, circularity and zero-waste: 3DP products from waste plastic bottles, *Composites Part C*. 2024. Vol. 14, 100463. <https://doi.org/10.1016/j.jcomc.2024.100463>.
- ¹⁴ Manu Srivastava, Sandeep Rathee, Vivek Patel, Atul Kumar, Praveennath G. Koppad, A review of various materials for additive manufacturing: Recent trends and processing issues, *Journal of Materials Research and Technology*, Volume 21, 2022, 2612-2641, <https://doi.org/10.1016/j.jmrt.2022.10.015>.
- ¹⁵ Jörg Bromberger, Julian Ilg, and Ana Maria Miranda. The mainstreaming of additive manufacturing. McKinsey & Company. 2022 (Accessed 1.2.2024)

¹⁶ The Top Challenges in Additive Manufacturing and How to Overcome Them. SyBridge Technologies. October 26, 2022 (Accessed 1.2.2024)

¹⁷ 10 of the Biggest Challenges in Scaling Additive Manufacturing for Production in 2020 [Expert Roundup]. AMFG Autonomous Manufacturing. 2022 (Accessed 1.2.2024)

¹⁸ Grant Guggenbiller, Scott Brooks, Olivia King, Eric Constant, David Merckle, Andrew C Weems. 3D Printing of Green and Renewable Polymeric Materials: Toward Greener Additive Manufacturing. ACS Appl. Polym. Mater. 2023. <https://doi.org/10.1021/acsapm.2c02171>

¹⁹ <https://www.basf.com/global/en/media/news-releases/2018/04/p-18-161.html> (Accessed 1.2.2024)

²⁰ <https://www.infinam.com/en/3d-printing-materials> (Accessed 1.2.2024)

²¹ Oliver Johnson Stratasys launches new FDA-cleared resin for dental 3D printing TrueDent resin is Stratasys' first FDA-cleared medical device. 2023 (Accessed 1.2.2024)

²² Fabio A. Cruz Sanchez, Hakim Boudaoud, Mauricio Camargo, Joshua M. Pearce. Plastic recycling in additive manufacturing: A systematic literature review and opportunities for the circular economy, Journal of Cleaner Production 2020, 264, 121602. <https://doi.org/10.1016/j.jclepro.2020.121602>.

²³ ISO 14040:2006. (2006). Environmental management — Life cycle assessment — Principles and framework. Geneva, Switzerland: International Organization for Standardization.

²⁴ ISO 14044:2006. (2006). Environmental management — Life cycle assessment — Requirements and guidelines. Geneva, Switzerland: International Organization for Standardization.

²⁵ Müller Leonard Jan , Kätelhön Arne , Bachmann Marvin , Zimmermann Arno , Sternberg André , Bardow André. A Guideline for Life Cycle Assessment of Carbon Capture and Utilization. Frontiers in Energy Research. 2020, Vol. 8. <https://doi.org/10.3389/fenrg.2020.00015>

²⁶ Adisa Azapagic, Roland Clift, Allocation of environmental burdens in multiple-function systems, *Journal of Cleaner Production*, Volume 7, Issue 2, 1999, 101-119, [https://doi.org/10.1016/S0959-6526\(98\)00046-8](https://doi.org/10.1016/S0959-6526(98)00046-8).

²⁷ Simon Fowell, LCA and LCCA – Are you sure you know the difference? 2021 (Accessed 23.1.2024)

²⁸ Marcella Ruschi Mendes Saade, Ammar Yahia, Ben Amor, How has LCA been applied to 3D printing? A systematic literature review and recommendations for future studies, *Journal of Cleaner Production*, Volume 244, 2020, 118803, <https://doi.org/10.1016/j.jclepro.2019.118803>.

²⁹ Samruddha Kokare, J.P. Oliveira, Radu Godina, Life cycle assessment of additive manufacturing processes: A review, *Journal of Manufacturing Systems*, Volume 68, 2023, 536-559, <https://doi.org/10.1016/j.jmsy.2023.05.007>.

³⁰ SLS vs. DMLS: Differences and Comparison. <https://www.xometry.com/resources/3d-printing/sls-vs-dmls-3d-printing/> (Assessed 11.3.2024)

³¹ Fidan, Ismail, Vivekanand Naikwadi, Suhas Alkunte, Roshan Mishra, and Khalid Tantawi. 2024. "Energy Efficiency in Additive Manufacturing: Condensed Review" *Technologies* 12, no. 2: 21. <https://doi.org/10.3390/technologies12020021>

³² ISO/ASTM 52910:2018. Additive manufacturing—Design—Requirements, guidelines and recommendations.

³³ P. Ramesh and Sekar Vinodh. Analysis of factors influencing energy consumption of material extrusion-based additive manufacturing using interpretive structural modelling, *Rapid Prototyping Journal*, 2021, 27, (7), 1363-1377. <https://doi.org/10.1108/RPJ-05-2020-0100>

³⁴ Vidakis, Nectarios, Markos Petousis, Nikolaos Mountakis, Amalia Moutsopoulou, and Emmanuel Karapidakis. 2023. "Energy Consumption vs. Tensile Strength of Poly[methyl methacrylate] in Material Extrusion 3D Printing: The Impact of Six Control Settings" *Polymers* 15, no. 4: 845. <https://doi.org/10.3390/polym15040845>

- ³⁵ Fidan, Ismail, Vivekanand Naikwadi, Suhas Alkunte, Roshan Mishra, and Khalid Tantawi. 2024. "Energy Efficiency in Additive Manufacturing: Condensed Review" *Technologies* 12, no. 2: 21. <https://doi.org/10.3390/technologies12020021>
- ³⁶ JIANG, Sheng. Processing rate and energy consumption analysis for additive manufacturing processes: Material extrusion and powder bed fusion. 2017. PhD Thesis. Massachusetts Institute of Technology.
- ³⁷ Top, N., Sahin, I., Mangla, S. K., Sezer, M. D., & Kazancoglu, Y. (2023). Towards sustainable production for transition to additive manufacturing: a case study in the manufacturing industry. *International Journal of Production Research*, 61(13), 4450-4471.
- ³⁸ Garcia, F. L., Nunes, A. O., Martins, M. G., Belli, M. C., Saavedra, Y. M., Silva, D. A. L., & Moris, V. A. D. S. (2021). Comparative LCA of conventional manufacturing vs. additive manufacturing: the case of injection moulding for recycled polymers. *International Journal of Sustainable Engineering*, 14(6), 1604-1622.
- ³⁹ Ramadugu, S., Ledella, S., Gaduturi, J. et al. Environmental life cycle assessment of an automobile component fabricated by additive and conventional manufacturing. *Int J Interact Des Manuf* 18, 847–858 (2024). <https://doi.org/10.1007/s12008-023-01532-0>
- ⁴⁰ KELLENS, Karel; Yasa, Evren; Dewulf, Wim; Duflou, Joost R. Environmental assessment of selective laser melting and selective laser sintering. *methodology*, 2010, 4(5).
- ⁴¹ Dotchev, K. and Yusoff, W. (2009), "Recycling of polyamide 12 based powders in the laser sintering process", *Rapid Prototyping Journal*, Vol. 15 No. 3, pp. 192-203.
- ⁴² Hari P.N. Nagarajan, Karl R. Haapala. Environmental Performance Evaluation of Direct Metal Laser Sintering through Exergy Analysis, *Procedia Manufacturing*, 2017, 10, 957-967. <https://doi.org/10.1016/j.promfg.2017.07.087>.
- ⁴³ van Sice, C., & Faludi, J. (2021). Comparing environmental impacts of metal additive manufacturing to conventional manufacturing. *Proceedings of the Design Society*, 1, 671-680. <https://doi.org/10.1017/pds.2021.67>

⁴⁴ Fabricio Leon Garcia, Andréa Oliveira Nunes, Mariane Guerra Martins, Maria Cristina Belli, Yovana M.B. Saavedra, Diogo Aparecido Lopes Silva & Virgínia Aparecida da Silva Moris (2021) Comparative LCA of conventional manufacturing vs. additive manufacturing: the case of injection moulding for recycled polymers, *International Journal of Sustainable Engineering*, 14:6, 1604-1622, DOI: [10.1080/19397038.2021.1990435](https://doi.org/10.1080/19397038.2021.1990435)

⁴⁵ Jung S, Kara LB, Nie Z, Simpson TW, Whitefoot KS. Is Additive Manufacturing an Environmentally and Economically Preferred Alternative for Mass Production? *Environ Sci Technol*. 2023 Apr 25;57(16):6373-6386. doi: 10.1021/acs.est.2c04927. Epub 2023 Apr 17. PMID: 37066969; PMCID: PMC10134501.

⁴⁶ Samruddha Kokare, J.P. Oliveira, Radu Godina, Life cycle assessment of additive manufacturing processes: A review, *Journal of Manufacturing Systems*, 2023, 68, 536-559. <https://doi.org/10.1016/j.jmsy.2023.05.007>.

⁴⁷ Aruanno, Beatrice. 2024. "EcoPrintAnalyzer: Assessing Sustainability in Material Extrusion Additive Manufacturing for Informed Decision-Making" *Sustainability* 16, no. 2: 615. <https://doi.org/10.3390/su16020615>

⁴⁸ Sola, A.; Rosa, R.; Ferrari, A.M. Environmental Impact of Fused Filament Fabrication: What Is Known from Life Cycle Assessment? *Polymers* 2024, 16, 1986. <https://doi.org/10.3390/polym16141986>

⁴⁹ OU, Yating, et al. Material extrusion additive manufacturing of novel lightweight collinear stayed polymer lattices. *International Journal of Mechanics and Materials in Design*, 2024, 1-17.

⁵⁰ Presciutti A, Gebennini E, Liberti F, Nanni F, Bragaglia M. Comparative Life Cycle Assessment of SLS and mFFF Additive Manufacturing Techniques for the Production of a Metal Specimen. *Materials (Basel)*. 2023 Dec 23;17(1):78. doi: 10.3390/ma17010078. PMID: 38203933; PMCID: PMC10779992.

⁵¹ Charlotte Roux, Kateryna Kuzmenko, Nicolas Roussel, Romain Mesnil, **Adélaïde** Feraille. Life cycle assessment of a concrete 3D printing process. The International Journal of Life Cycle Assessment, 2023, 28, 1-15. <https://doi.org/10.1007/s11367-022-02111-3>

⁵² Li, Jujube. 2015. A Comparative Meta-Life Cycle Inventory Analysis: Energy and Water Consumption of 3D Printing Methods vs. Conventional Manufacturing in Clothing Production. Master's thesis, Harvard Extension School. <https://dash.harvard.edu/handle/1/24078377> (Assessed 13.3.2024)

⁵³ Beth McGrath, Jaymes Hanna, Runze Huang, Amar Shivdasani. 3D opportunity for life cycle assessments Additive manufacturing branches out. Deloitte University Press, an imprint of Deloitte Development LLC.

https://www2.deloitte.com/content/dam/insights/us/articles/additive-manufacturing-in-lca-analysis/DUP_719-3D-opportunity-life-cycle_MASTER.pdf (Assessed 13.3.2024).

⁵⁴ Bhasin, Shallu; Singari, Ranganath M.; Arora, Pawan Kumar; Kumar, Harish. Implications of Additive Manufacturing on Supply Chain Management. 2024. Journal of Industrial Integration and Management. Vol.9, 117-131. DOI: 10.1142/S2424862221500299

⁵⁵ Woldesilassiea, Tekalign Lemma, Hirpa G. Lemu, and Endalkachew Mosisa Gutema. 2024. "Impacts of Adopting Additive Manufacturing Process on Supply Chain: Systematic Literature Review" Logistics 8, no. 1: 3. <https://doi.org/10.3390/logistics8010003>

⁵⁶ Samruddha Kokare, João Pedro Oliveira, Radu Godina. 18 - Life cycle assessment and economics of additive manufacturing processes, Editor(s): Sanjay Mavinkere Rangappa, Vinod Ayyappan, Suchart Siengchin. In Additive Manufacturing Materials and Technologies, Additive Manufacturing Materials and Technology, Elsevier. 2024, 445-473. <https://doi.org/10.1016/B978-0-443-18462-8.00018-0>.

⁵⁷ file:///C:/Users/music_b/Downloads/%C3%96ko_Performance_Fertigungstechnologien.pdf (assessed on 13.9.2024)

⁵⁸ <https://3dprint.com/284243/ge-aviation-announces-100000th-3d-printed-fuel-nozzle-shipped-from-auburn-plant/>

⁵⁹ <https://www.scielo.br/j/jatm/a/rrW5H7FGWtpDrbJSPtZTJ7d/?format=pdf&lang=en>

⁶⁰ <https://3dprint.com/305846/siemens-and-ornl-3d-print-25-pound-turbine-blade-with-waam/>

⁶¹ Liu, Xuan, Xingguo Han, Guofu Yin, Xiaohui Song, and Lixiu Cui. 2023. "Design and Processing of Gas Turbine Blades Based on Additive Manufacturing Technology" *Micromachines* 14, no. 9: 1675. <https://doi.org/10.3390/mi14091675>

⁶²https://www.researchgate.net/publication/327326826_Additive_Manufacturing_for_the_Manufacture_of_Gas_Turbine_Engine_Components_Literature_Review_and_Future_Perspectives

⁶³ <https://www.mdpi.com/2504-4494/6/1/16>

⁶⁴ <https://www.additivemanufacturing.media/articles/stryker-using-additive-for-implants>
(Accessed 31.7.2024)

⁶⁵ Meng Meng, Jinzuo Wang, Huagui Huang, Xin Liu, Jing Zhang, Zhonghai Li. 3D printing metal implants in orthopedic surgery: Methods, applications and future prospects, *Journal of Orthopaedic Translation*, 2023, Vol. 42, 94-112, <https://doi.org/10.1016/j.jot.2023.08.004>.

⁶⁶ <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8059996/>

⁶⁷ Zhang Jifa , Lu Shizhu , Yang Yadie , Liu Yiwen , Guo Yuqing , Wang Hongrui. Efficacy of auxetic lattice structured shoe sole in advancing footwear comfort—From the perspective of plantar pressure and contact area. *Frontiers in Public Health*, 2024, Vol. 12. DOI=10.3389/fpubh.2024.1412518 doi: [10.3389/fpubh.2024.1412518](https://doi.org/10.3389/fpubh.2024.1412518)

⁶⁸ <https://doi.org/10.1017/dsi.2019.76>

⁶⁹<https://doi.org/10.1016/j.promfg.2021.06.035>

⁷⁰ <https://www.dental-tribune.com/c/align-technology-switzerland-gmbh/news/3d-printing-acquisition-may-help-align-technology-to-break-the-mould/>

⁷¹ <https://www.wilhelmsen.com/ships-service/digital-ventures-mp/3d-printing-offering-a-stronger-and-more-resilient-supply-chain-for-spare-parts/>

⁷² https://link.springer.com/chapter/10.1007/978-3-031-32280-8_27

⁷³ <https://www.mdpi.com/2071-1050/15/20/15081>

⁷⁴ Olivier Jolliet, Manuele Margni, Raphaël Charles, Sébastien Humbert, Jérôme Payet, Gerald Rebitzer, Ralph Rosenbaum. IMPACT 2002+: A new life cycle impact assessment methodology. The International Journal of Life Cycle Assessment. 2003, 8, 324–330. <https://doi.org/10.1007/BF02978505>

⁷⁵ Mark A. J. Huijbregts, Zoran J. N. Steinmann, Pieter M. F. Elshout, Gea Stam, Francesca Verones, Marisa Vieira, Michiel Zijp, Anne Hollander, Rosalie van Zelm. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level, The International Journal of Life Cycle Assessment. 2017, 22, 138–147 (2017). <https://doi.org/10.1007/s11367-016-1246-y>

⁷⁶ Climate Change Division, Office of Atmospheric Programs (MC-6207A), U.S. Environmental Protection Agency, 1200 Pennsylvania Ave NW, Washington, DC 20460. Understanding Global Warming Potentials. <https://www.epa.gov/ghgemissions/understanding-global-warming-potentials>. 2023. (accessed 27/2/2024)

⁷⁷ Pettersson, Ante B. V., Rosa Maria Ballardini, Marc Mimler, Phoebe Li, Mika Salmi, Timo Minssen, Ian Gibson, and Antti Mäkitie. 2024. "Core Legal Challenges for Medical 3D Printing in the EU" *Healthcare* 12, no. 11: 1114. <https://doi.org/10.3390/healthcare12111114>

⁷⁸ <https://slcontrols.com/en/where-do-we-stand-with-the-new-eu-mdr-additive-manufacturing-and-customised-medical-devices/> (assessed at 30.8.2024)